Elementary, Economic Experiments in Physics

by Reginald F. Melton

II. teacher's guide

Teacher's Guide

to

ELEMENTARY, ECONOMIC EXPERIMENTS IN PHYSICS

by

REGINALD F. MELTON

Table of Contents

FOREWORD

'Triple E Physics' is basically a package consisting of four guides: Student Guide, Teacher's Guide, Apparatus Guide and Administrator's Guide.

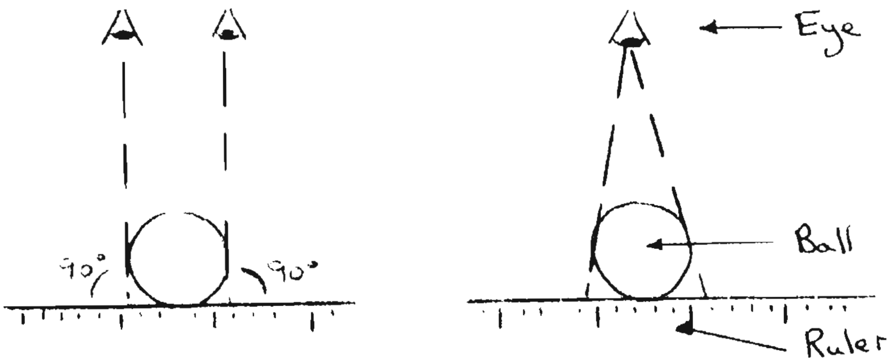
The Teacher's Guide contains relevant comments and suggestions, together with detailed results of actual experiments, insuring that teachers can proceed with new materials with confidence.

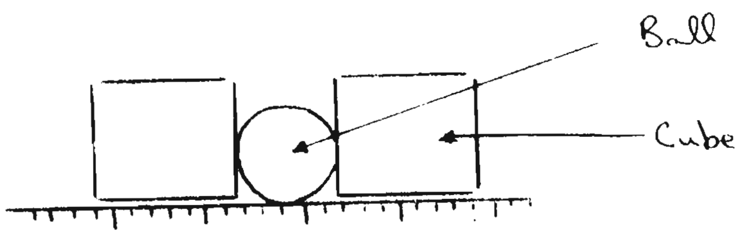
Details of related laboratory plans, workshop facilities, methods of apparatus production and overall planning are to be found in the Administrator's Guide.

1.10 DISTANCE

1.11 Accuracy and Significance

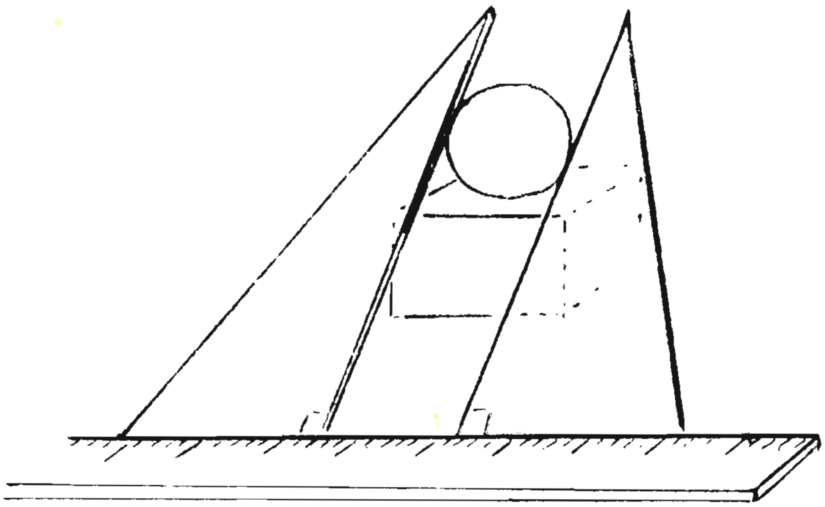
(i) Ping pong balls will serve the purpose of this experiment, but items such as tennis balls or basket balls could prove to be interesting additional items for measurement. If possible let the student discover his own inaccuracies of measurement, and how to use cubes or set squares for greater accuracy.





In the first instance the student will probably automatically use one eye only when reading the scale, but you can suggest that he observes the reading with first one eye and then the other to see what effect it has on the reading. It will not be long before the student sees for himself the problem of parallax, and the need to view the scale at right angles, with one eye only, for every reading.

The student will probably have very little difficulty in deciding how to use the cubes to improve the accuracy of his readings, but may need some guidance with the set squares. However, do try to guide him rather than show him how to do this. Ask leading questions, and he will begin to think for himself how the set square might be used to advantage.



(ii) Divide the students into 4 or 5 groups, and give each group a different floor or wall width to measure, and then compare results within each group. Thus one group might measure a given width, and the individuals within the group (5 in this case) will come up with a series of results something like the series indicated below. Put the results on the board, and discuss them. Although students might try to measure the width to the nearest millimeter it becomes clear that the method of measurement involves inaccuracies of several millimeters. It is therefore meaningless to express the result to the nearest millimeter.

650.3 cms
648.7 cms
652.1 cms
651.4 cms
652.8 cms

It is better to express each reading to the nearest cm, expressing the finding of the group as a whole as 651 $\pm$ 2 cms. In other words even the last figure quoted is subject to a possible error of $\pm$ 2 cms.

650 cms
649 cms
652 cms
651 cms
653 cms

(iii) Measurement of the thickness of a sheet of paper, as a result of measuring the thickness of 50 sheets, might be treated in very much the same way as above.

Students might well question why measurements are being made in metric units, and a brief discussion might be of value at this stage. The following historical facts may be of interest.

The inch was originally defined as the width of the thumb at the base of the nail, while the yard was defined as the distance from nose to thumb with the arm stretched out horizontally to one side. With the need for standardization a "standard rod, 1 yard long" was kept for reference in London.

The meter was defined as one ten millionth of the shortest distance between the North and South Poles. A "standard rod, 1 meter long" is kept for reference in Paris. The greater convenience of the decimal system should be pointed out.

1.12 Thickness of Oil Films

(i) The first part of the experiment is intended to show the need for extreme cleanliness with film experiments, and also to show that in the case of olive oil or oleic acid the film remains on the water surface.

When one small drop of oil is transferred to the water the chalk dust is pushed away from the wire as the oil spreads out. If the surface is then recovered with chalk dust, and a further oil drop added the chalk remains stationary. We might say that we have contaminated the surface with oil from the first drop.

When further oil drops are poured onto the water they can be seen to drop just below the surface before rising and floating. There is no question of the oil mixing with the water. In other words oil added to the water remains on the surface and spreads out without mixing with the water.

The importance of cleanliness may be further emphasized by taking a clean ripple tank once again and adding water and powdering the surface. Rub your fingers through your hair, and then dip one finger into the water. The grease on your finger will behave in just the same way as an oil drop in spreading out over the water surface.

The experiment, as it has been described, is crude in that measurement of the diameter of the oil drop is particularly rough. The result therefore only gives an indication of how thin an oil film can become.

In actual fact an oil film will spread out until it becomes a single molecular layer of oil floating on the water. Performed under more rigorous conditions, and with greater accuracy, the result would therefore indicate the order of magnitude of the size of a molecule. An experiment performed by students under the conditions described produced the following results.

$$r_1 = 0.5 \pm 0.02 \text{ cms}$$

$$r_2 = 5.0 \pm 0.5 \text{ cms}$$

Hence thickness of film is given by:

$$t = \frac{4\, r_1^{3}}{3\, r_2^{2}} \text{ cms}$$

$$= 6.6 \times 10^{-6} \text{ cms}$$

1.13 Triangulation

(i) This experiment should illustrate to the student the importance of methodically tabulating data. Let him record the readings in any way he chooses at first. He will then appreciate the value of a table such as that given below.

x_2	x_1	h_2	h_1	x_2/x_1	h_2/h_1
50	10	10	2	5	5
50	20	10	4	2.5	2.5
50	30	10	6	1.7	1.7
50	40	10	8	1.25	1.25
cms	cms	cms	cms		

You might omit the last two columns from the table at the start, and ask students whether they can see any relationship relating x_1 and h_1. The final columns might then be added to help the discussion. It should become clear that for any fixed setting of the apparatus that:

$$\frac{x_2}{x_1} = \frac{h_2}{h_1}$$

(ii) The following results were obtained in the determination of the height of the wall. All readings obtained for the first experiment at a distance of 4 meters are indicated with small letters, while readings for the second experiment at a distance of 5 meters are indicated with capital letters.

1st Experiment:

When $x_2 = 400$ cms

$x_1 = 20$ cms

$h_1 = 20$ cms

$$h_2 = h_1 . \frac{x_2}{x_1} = 20 \times \frac{400}{20} = 400 \text{ cms}$$

2nd Experiment:

When $X_2 = 500$ cms

$X_1 = 20$ cms

$H_1 = 16$ cms

$$H_2 = H_1 . \frac{X_2}{X_1} = 16 \times \frac{500}{20} = 400 \text{ cms}$$

The same result is obtained at either distance. Of course the results need not be exactly the same, and this would not normally be expected due to the inaccuracies involved.

Let us suppose that the above experiment had been performed without noticing the distance to the wall in the first part was 4 meters, but that the increased displacement of 1 meter was recorded before repeating the experiment.

The results might then have been tabulated as follows:

3rd Experiment:

When $x_2 = ? \quad h_2 = ?$

$$x_1 = 20 \text{ cms}$$

$$h_1 = 20 \text{ cms}$$

$$x_2 = \frac{h_2}{h_1} \cdot x_1$$

$$x_2 = h_2 \quad \_\_\_\_\_(1)$$

On moving the triangulation apparatus:

$$X_2 = x_2 + 100 \quad \text{while } H_2 = h_2 = ?$$

$$X_1 = 20 \text{ cms}$$

$$H_1 = 16 \text{ cms}$$

$$H_2 = H_1 \cdot \frac{X_2}{X_1}$$

$$h_2 = \frac{H_1 (x_2 + 100)}{X_1} \quad \text{where } x_2 = h_2 \text{ from (1)}$$

$$+ \frac{16 (h_2 + 100)}{20}$$

Hence:

$$h_2 = 400 \text{ cms} \quad \_\_\_\_\_(2)$$

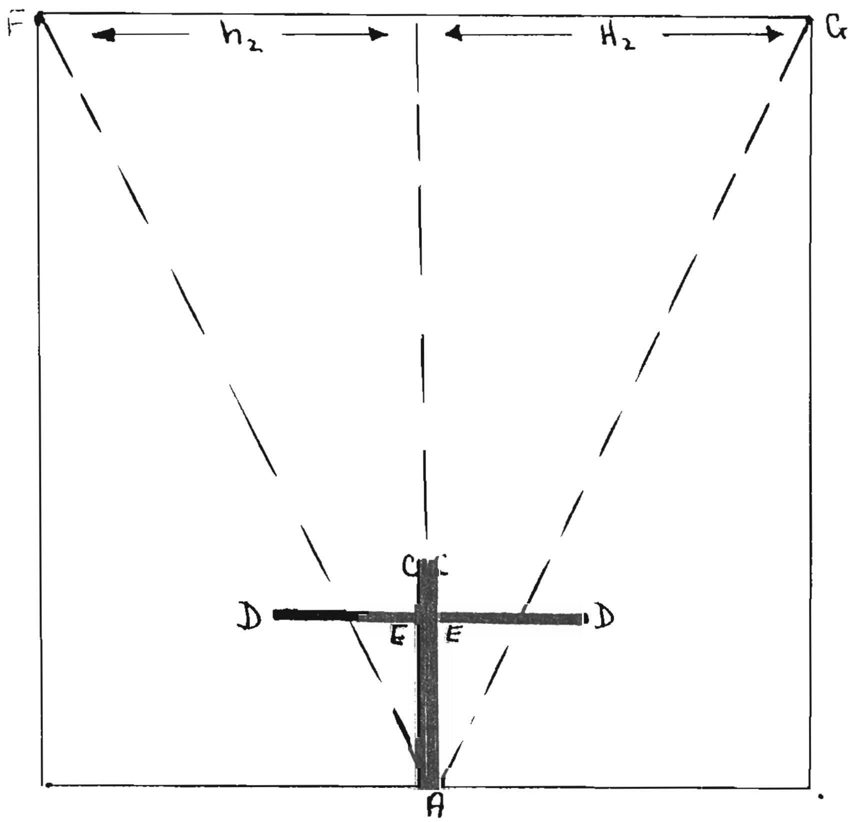
Similarly substituting the value of h_2 in equation (1)

$$x_2 = 400 \text{ cms} \quad \_\_\_\_\_(3)$$

This system of determing the height of an object also determines the distance between the object and observer. However, it should be noted that for reasonable results the shift in position of the observer should be comparable with the distance between the observer and object. Thus in the above example the shift is 1 meter compared with an original distance of 4 meters. If the original distance had been 4,000 meters a shift of 1 meter would have had no effect on the two readings, but a shift of 40 meters would probably be adequate.

It is important that the student should not be depressed by mathematics at this stage, and it should be pointed out that the only reason for extending this problem to determine two unknowns is that it gives the student some idea of how surveys might be conducted outside by simple triangulation techniques.

(iii) In determining the width of the classroom wall this must be done in two stages for it must be remembered that the upright ED(h_1) of the triangulation apparatus must be parallel to the object (the wall) for all readings. Referring to the diagram it is necessary to determine h_2 and H_2 separately, adding the two together for the final result. It is not possible to point the base (AC) of the apparatus in the direction AF, taking a reading in the direction AG, for in this case the upright DE and object FG would not be parallel.



View of classroom from above

1.14 Volume

Students will be surprised to find that the graduated cylinder indicates the volumes of the two spheres as being 1 cc and 2 cc respectively. Comparing the 1 cc sphere with a 1 cc cube, the latter seems much bigger, but on checking the graduations by lowering the displacement block into the water it is realized that they are correct. The illusion is caused by the surface area of the sphere being very much smaller than that of the cube. In fact, the surface area of a given volume of a substance is a minimum when the substance takes on the shape of a sphere.

1.20 MASS

1.21 The Simple Balance

(i) The aim of this introduction is to give the student the idea that mass is a quantity of matter, and at the same time to let him see how units of mass might have first been introduced.

It is suggested that without the student's knowledge you count the number of nails which weigh 10 gms. If this is 30 you then start the experiment by asking him to make up piles of nails with 30 in each pile. It will then follow that the mass of modeling clay used to balance the 30 nails will weigh 10 gms, and this will prove to be useful in the later stages of the experiment.

Nails come in all sizes and it is suggested that the type chosen are such that between 20 and 30 make up 10 gms. If the nails are so small that 50 make up 10 gms the balance will not be sufficiently sensitive to the addition of each nail. Then in weighing out unit masses of the nails the student is quite likely to produce 48, 52 and so on instead of 50. On the other hand if the nails are big so that there are only 10 in 10 gms the student will be quite happy to count them rather than weigh them.

It is interesting at this stage to discuss with the student the weighing of coins in the bank as a rapid means of counting. They may not realize that this is a quick standard procedure. (They might also be interested to learn that the British Pound Sterling was given the name Pound to indicate that it was equivalent to a mass of one pound of silver).

(ii) A ball point pen or pencil will weigh between 10 and 20 gms, and it will be sufficient for the student to make this sort of comment from his first observation.

With the masses in the right hand pan weighing 15 gms it is quite possible that the scale reading might suggest 16 gms, indicating that the scale cannot predict more accurately than 1 part in 15.

One might also check the uniformity of the scale by adding nails to the right hand scale pan one after the other, and noting how many nails need to be

added to move the pointer through each division on the scale. Two sample sets of results are given below.

Movement of Pointer on Scale	Nails Added	
	Sample 1	Sample 2
0 to 1	3	4
1 to 2	3	2
2 to 3	3	3
3 to 4	3	2
4 to 5	3	4

(0 to 10 corresponds to 10 gms)

Results similar to those in Sample 1 suggest uniform sensitivity of the balance, while those in Sample 2 suggest a less uniform behavior pattern, and would indicate that the readings on the scale are only accurate to the nearest 1/3 gm. Hence 4 divisions would be treated as reading 4 ± 0.33 gms.

1.22 Microbalance

(i) Let's say that 10 sheets of bond paper weigh 30 gms.

Then:

1 sheet of paper (20 x 25 = 5,000 sq. cms) weighs 3 gms

1 sq. cm of bond paper weighs $\frac{3}{5,000}$ gms

or 0.006 gms

or 6 milligrams

Although this provides the student with a very convenient standard mass for his experiment you should point out the disadvantages of masses made from materials (paper, modeling clay, etc.) which deteriorate and change with wear and tear.

(ii) With the pivot close to the top surface of the straw the microbalance will be at its most stable. However, as the pivot is moved away from the top surface towards the middle of the straw the microbalance will become more sensitive.

In suggesting materials for weighing, two items were specifically mentioned for the bright students. In weighing a water drop a student may well note the change in mass as it evaporates, while weighing small pieces of wire, before and after they are heated, may enable a student to note a change in mass due to oxidation. The weighings should be suggested without further comment. Let the student discover the strange behavior for himself.

1.30 TIME

1.31 Simple Timing Devices

(i) and ii) The idea of introducing several simple timing devices is to indicate that the accuracy of any one device can only be assessed by comparison against another. In the first activity one might ask whether the rate of walking a given distance is more variable than the pulse rate being used to measure it. Both can be surprisingly steady, and could be used to measure crude intervals of time. Thus a student was timed as he walked 5 meters across a room on 3 successive occasions, and was noted to take 11, 12 and 12 pulse beats respectively.

(iii) This activity is designed to show how one can highlight the irregularities that may exist in a timing device. Two observers, A and B, recorded their pulse beats against 20 oscillations of the pendulum (fixed at a length of 25 cms). The results were as follows:

Condition of Observers	Pulse Beats Recorded By: A	B
A and B both sitting	22	29
A and B both sitting (a repeat)	22	29
A immediately after exercising, B still sitting	25	29
A once more sitting, B still sitting	20	29

The pulse rate remains amazingly steady, as indicated by observer B, so long as the experimenter remains sitting quietly. Activity clearly raises the pulse rate as is seen by observer B, whose pulse rate rose from 22 to 25. However, it drops rapidly back to normal, and in fact dropped below normal in this particular case a little time after the activity had ceased.

Suggest that the student checks his pulse rate at different times of the day, and at night when he is lying down.

(iv) The following results indicate the number of pulse beats recorded by observer B during 20 oscillations of different pendulum lengths. It follows that the rate of oscillation of the pendulum varies with its length, but while its length remains constant the rate of oscillation appears to be constant.

Pendulum Length	Pulse Beats per 20 Oscillations
10 cm	19, 19
25 cm	29, 29
50 cm	40, 39

(v) Varying the mass of the pendulum bob does not change the rate of oscillation. 20 oscillations of the pendulum were still noted to take 29 pulse beats.

The pendulum length was deliberately fixed at 25 cms in this experiment, for at this length the pendulum has a period of almost exactly 1 second.

1.32 Ticker Tape Timer

(i) In dropping an object from the table to the floor not even 1 oscillation of the pendulum is noted to occur. Other than saying that the time taken for the object to fall is less than a second it is impossible to even guess at what fraction of time elapsed.

It is of course possible to increase the rate of oscillation of the pendulum a little by shortening it, but a much more rapid vibration may be set up with the hacksaw blade. Unfortunately, it is impossible to count very rapid vibrations of the blade by visual means, and a mechanical means of counting such as that available with the ticker tape timer is required.

A student took 3 meters of ticker tape, and pulled it through the timer for exactly 3 seconds. He repeated the process three times in all, and recorded the number of ticks in each of the 5 seconds intervals as 154, 146, 150. The average number of ticks per 5 second interval was therefore 150, and the average rate of vibration of the timer 50 per second.

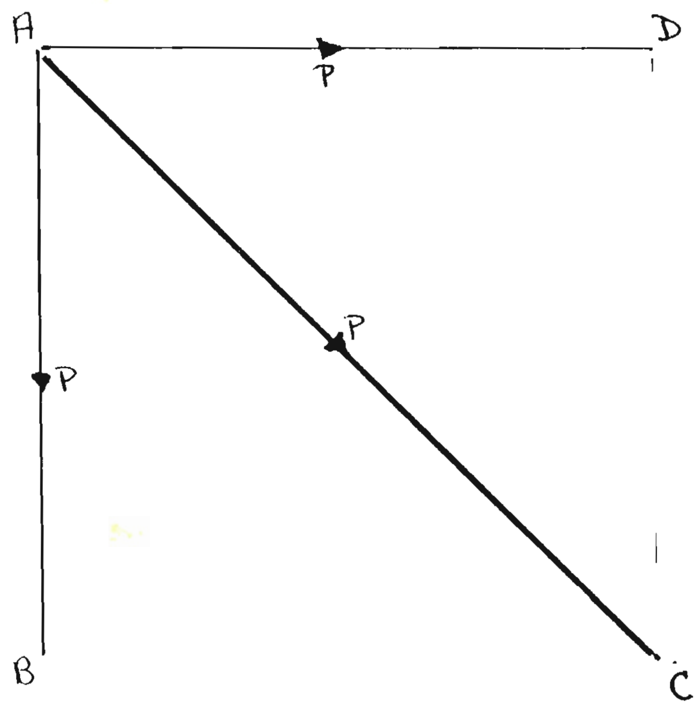
An object was then permitted to fall to the ground, and the time lapse recorded by the timer (averaged over 3 occasions) was 10 vibrations. It follows that the time of falling was 1/5 second.

1.40 FRAMES OF REFERENCE

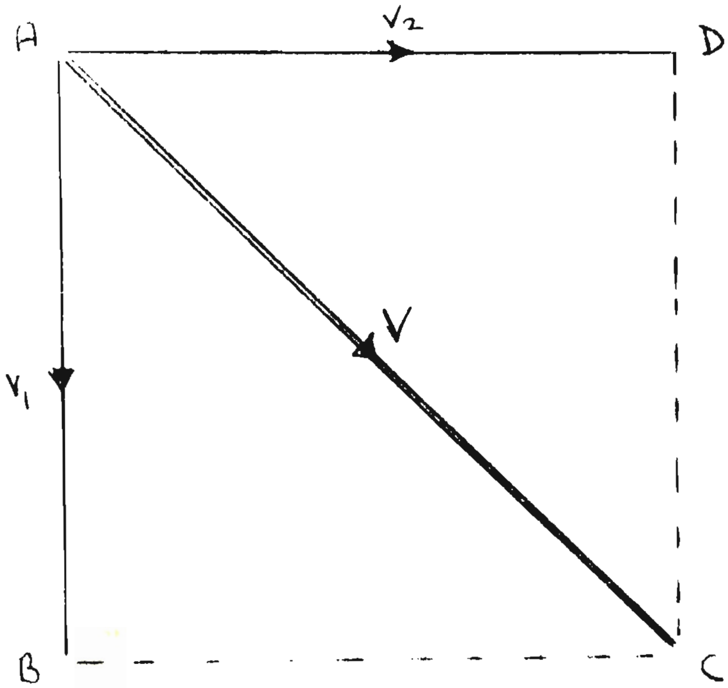
1.41 Relative Motion

(i) The first exercise is simply intended to clarify the student's concept of relative motion. In the first instance the motion of the pen (P) relative to the paper is in the direction A to B. In the second instance, although the motion of the sheet (S) of paper relative to the pen is in the opposite direction, the motion of the pen (P) relative to the paper remains in the same direction as in the first instance.

(ii) Our main concern is the drawing which emerges on sheet 2 as the result of combining two motions of the pen relative to sheet 2: a motion from A to B, and one from A to D. The result is a motion from A to C, the diagonal of the rectangle of which the two motions form adjacent sides.

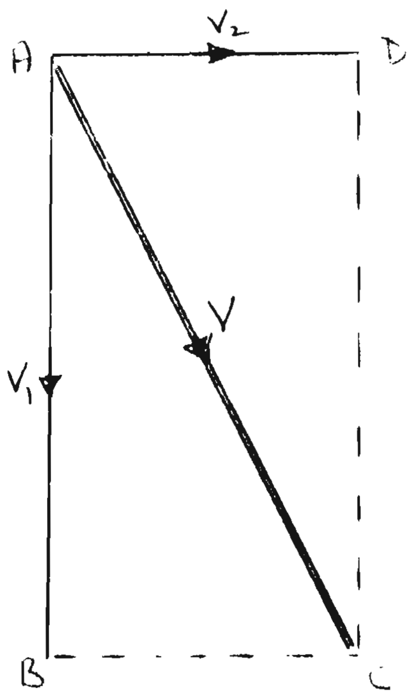


(iii) The diagrams overleaf illustrate the result of combining the motions in this series of activities. Let's imagine that in each instance the relative motions (AB and AD) to be combined were completed within exactly 1 second. The distances moved along AB and AD would also represent the velocities of the relative motions to be combined, while AC would represent the velocity of the resultant motion.



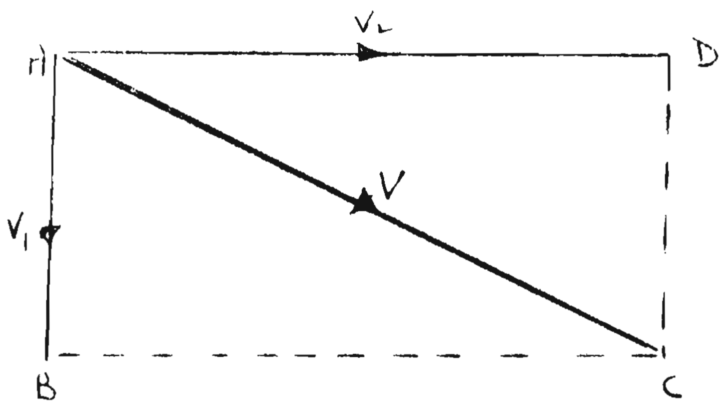
$v_1 = v_2$

$v^2 = v_1{}^2 + v_2{}^2$



$v_1 = 2v_2$

$v^2 = v_1{}^2 + v_2{}^2$



$v_1 = \frac{v_2}{2}$

$v^2 = v_1{}^2 + v_2{}^2$

2. Forces and Motion

2.10 INTRODUCTION TO FORCES

The first step is to help the student express what he means by a force. He should realize that it can cause objects to move, to be deformed or to break. He will also note that forces can be exerted by solids, liquids or gases.

2.11 Effect of Forces on Solids, Liquids and Gases

(i) Modeling clay (plasticene) and elastic sponge rubber illustrate two extreme patterns of behavior when subjected to forces. Modeling clay is deformed under stress and shows no tendency to take on its original shape when the stress is removed, whereas sponge rubber although deformed under stress returns to its original shape when the stress is removed. The two patterns of behavior are termed plastic and elastic behavior respectively.

(ii) Investigation with the metal strips will show that the lead behaves plastically and the steel elastically. The alloy shows an intermediate form of behavior. Under the action of small forces the alloy strip will bend, regaining its former shape on releasing the forces. Large forces however cause permanent deformation. The alloy thus behaves elastically under small forces and plastically under large forces. The same behavior is noted in most metals, but the transition point varies. Thus lead behaves elastically only under extremely small forces. Its behavior thus appears to be predominantly plastic. Steel on the other hand behaves elastically even under large forces. It is only when the forces are extremely large that plastic behavior or fracture is noted.

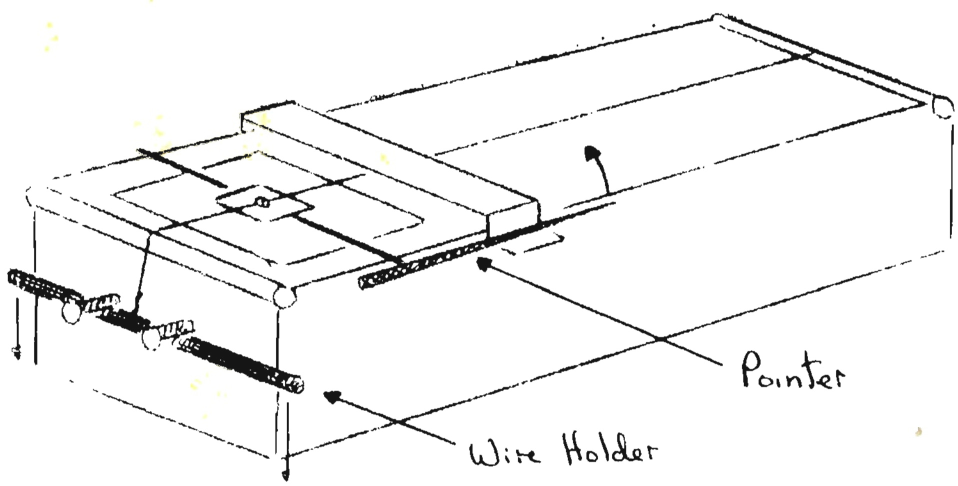
The student will be interested to note the elasticity of air in the syringe. He will be unable to conclude on the nature of the behavior of water, for the latter is almost incompressible, and observations of elasticity or otherwise are impossible with such a crude piece of apparatus.

The aim of this introduction is to help the student realize that elastic materials can indicate the magnitude of forces acting on a body by the degree of deformation occuring. A plastic material might indicate the degree of force exerted once, but since it remains deformed it is of no use for further measurement. It follows that of the materials available to date the sponge rubber, the steel strip and the syringe of air would appear to be the most elastic, and hence the most suitable for determining the magnitude of forces exerted on them.

(iii) With his eyes closed the student will have no difficulty in feeling the forces exerted by the stretched elastic band, and will readily indicate whether the band is being extended further or not.

He will also feel that there is a definite limit to the extension of the band, and that if he exceeds this limit the band will break. Holding the band under this maximum stress, or reapplying it 10 times, it will be noted that the band continuously increases its maximum length (and also its unstressed length). It in fact shows plastic behavior under large forces. Under small forces however its behavior appears to be reasonably elastic. This would suggest that elastic bands may be used to indicate the magnitude of forces so long as the force is not so great as to cause plastic deformation of the band.

(iv) When investigating materials for elasticity or plasticity they do not have to be in blocks or strips. They can take any form we choose such as wires or springs. The copper wire is particularly interesting for the student should be able to feel its plastic extension under the action of forces. Pulling a steel wire will produce no visible effect, and the student might conclude that no extension took place. It is therefore interesting to put the steel wire on the wire extender.



A force may be applied to the wire by pressing downwards on the wire holder. The pointer will exaggerate the resultant motion. The wire is noted to not only extend, but to return to its original length on removing the stress. It thus behaves elastically. It is of interest to replace the steel wire by a copper wire noting the initial elastic behavior of the copper under small forces, but plastic behavior under larger ones.

(v) Extending the copper spring to the 20 and then 30 cm mark will cause permanent extension of the spring, the extension being greater as a result of the stretching to the 30 cm mark. If the spring is extended to the 40 cm mark, and the stress then removed, the unstressed length will approach, or exceed, the 20 cm mark, and the student will have no difficulty in pointing out that the force holding the spring at the 20 cm mark cannot be the same as that which caused this extension at the beginning of the experiment.

The behavior of the steel spring is quite different. Even when extended to the 30 cm mark it still returns to its original length. Large forces always produce large extensions and small forces small extensions. Of course if the forces exerted becomes too large the spring will ultimately show a degree of plastic behavior. However, it follows that a steel spring is a good device for indicating the magnitude of a force so long as the forces exerted are not so great as to cause plastic deformation.

Any material which displays elastic behavior (elastic bands, copper and steel springs, air) may be used to measure the order of magnitude of forces so long as the elastic limit is not exceeded. Steel springs exhibit particularly good elastic properties and have a relatively high elastic limit, and for this reason are commonly found in most laboratories for measuring forces.

If materials are listed in order of increasing elasticity or decreasing plasticity, they will fall into the same order, whether the observations were made on metal strips, on wires or some other form of the material. The student therefore should not have much difficulty in suggesting that since lead and steel show plastic and elastic forms of behavior respectively, that a lead ball should not rebound much from a lead surface, whereas a steel ball should rebound strongly from a steel surface. This hypothesis is confirmed using the rebound apparatus.

2.12 Normality of State of Rest and Motion

(i) The force required to maintain a constant motion is less for one block than for two, and is even less when rollers are used beneath the block. It would seem that friction between the blocks and table surface opposes the motion.

(ii) Friction between the table surface may be reduced by the use of rollers, or by making the body itself spherical (ball bearing). When friction is reduced to a minimum (air puck) it is seen that a body tends to continue in motion (or rest) as a normal state of existence which does not change unless external forces (e.g., friction) act on the body. The student should recognize that friction is likely to be present in many of his experiments, and must be taken into account. It is difficult to think of motions completely unaffected by friction, and for examples one probably has to turn to the motion of satellites about the Earth and that of planets about the Sun.

2.13 Contact Forces, Action Forces and Friction

(i) The falling sheet of paper is clearly affected by the friction of the air. The larger the area of the paper (perpendicular to the direction of motion) the greater the effect of friction.

(ii) Blowing horizontally beneath the paper lifts it into a horizontal plane, but surprisingly blowing horizontally above the paper produces the same lift effect.

(iii) Dropping small ball bearings simultaneously from the same height it will be noted that the ball bearing falling through water, drops more slowly than that falling in air. At this point the student should not have much difficulty in indicating that the order of magnitude of frictional forces encountered are greater in liquids than in gases, and greater still in relation to solids.

(iv) and (v) These two activities illustrate that magnetic and electrostatic forces can be exerted without actual contact between the bodies concerned.

(vi) Clearly a stone falls straight past a basket ball without being deflected. However, a little logic shows that this is not the case when a larger mass than the basket ball (e.g., the Earth) is involved, for we see the force of gravity pulling bodies towards the center of the Earth.

2.14 Action and Reaction

(i) When the two magnets are held together and released simultaneously they push each other sideways the same distance away from the starting position. A pushes B, but there is an equal and opposite reaction of B pushing on A.

Although it is possible to hold one of the magnets stationary the distance the other is pushed away is just the same as when both are released simultaneously. Regardless of whether one of the magnets is held or not this suggests that each pushes equally strongly on the other.

(ii) The same phenomenon is noted with the two plastic strips, each pushing the other to an equal extent. In the case of the plastic strip and paper there is a force of attraction pulling the two together.

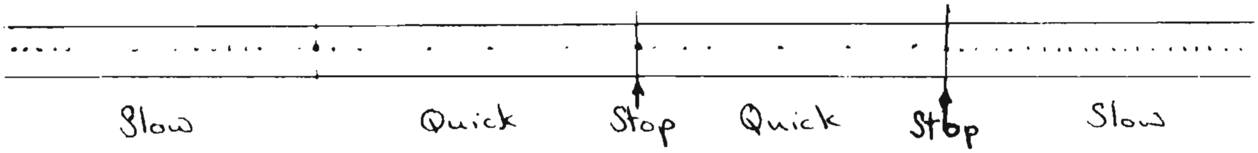
(iii) The extension of the spring with two equally strong students pulling it will be the same as when only one of the student pulls it at one end and the spring is held by the wall at the other. The only conclusion possible is that the action of the student creates an equal and opposite reaction from the wall.

When the students placed at either end of the spring are equally strong the spring is extended, but does not move towards one student or the other. However, when one student is stronger than the other the spring is pulled in the direction of the stronger student. It follows that equal and opposite forces may deform a body but will not move it, and that a body must be subjected to unequal forces if motion is to result.

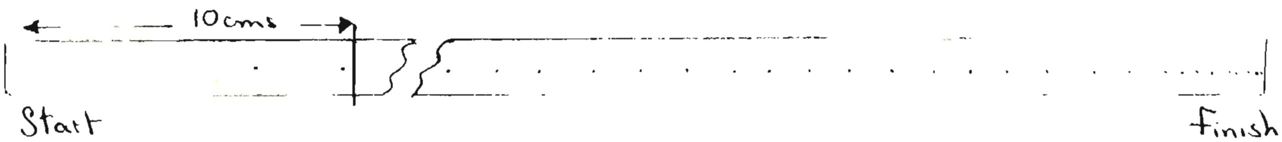
2.20 MOTION

2.21 Analyzing Motion

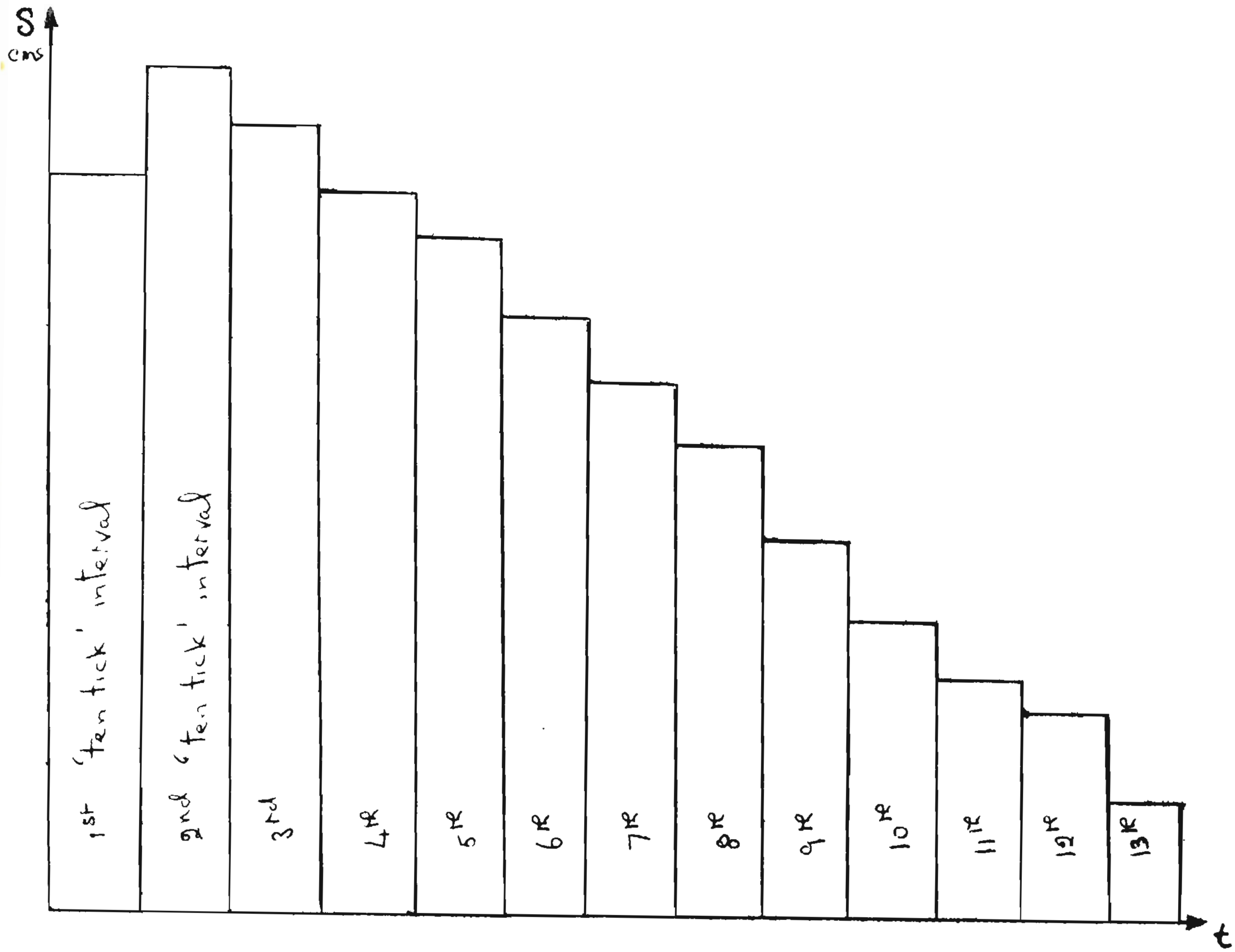
(i) The ticker tape markings due to variable motion would be similar to those indicated below.



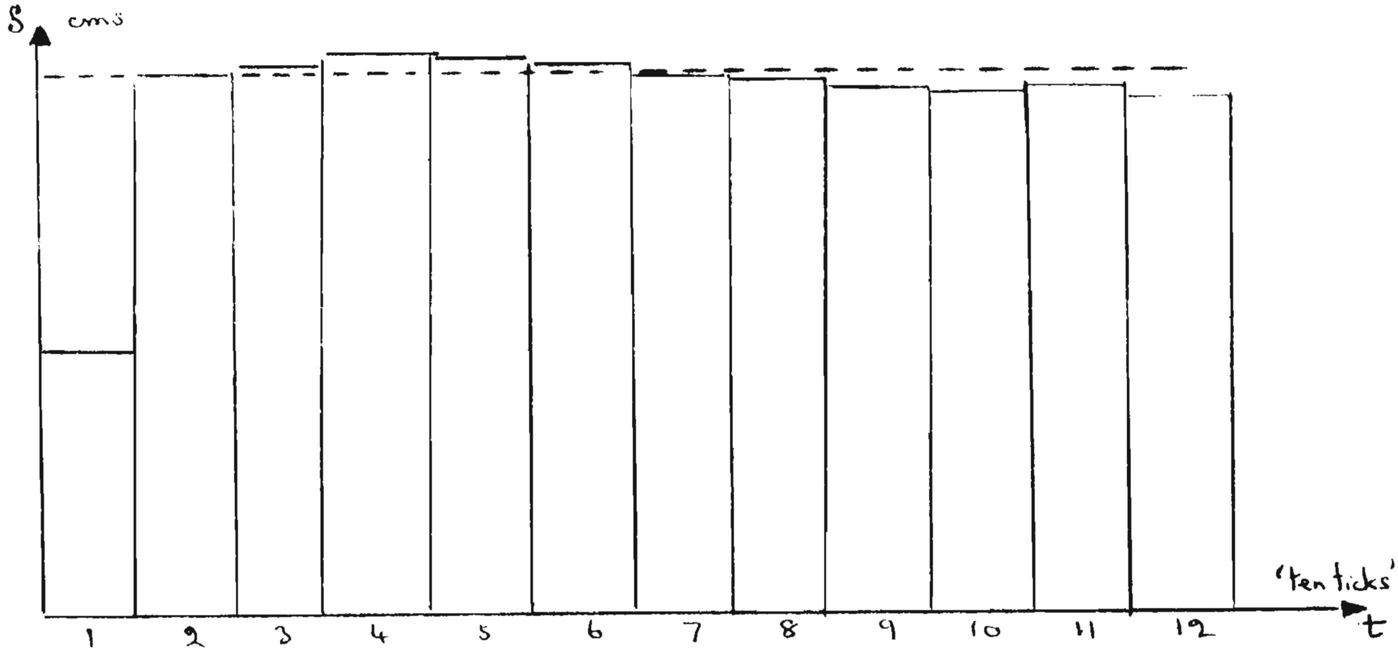
(ii) A 10 cm extension of the chain of rubber bands was found just sufficient to push the cart to the end of the plane. On studying the ticker tape it was noted that the first 10 cms of motion indicated an increasing speed while the elastic band accelerated the cart, and thereafter the motion became progressively slower under the effect of friction.



In creating a graph to illustrate the nature of the motion any starting point may be chosen, and generally this is after the first few overlapping dots which are difficult to separate or count. This in no way affects the general analysis. A typical graph is recorded overleaf. For two 'ten tick' intervals the speed increased under the action of the chain of elastic bands, but in the remaining eleven intervals it slowed down progressively under the action of friction.



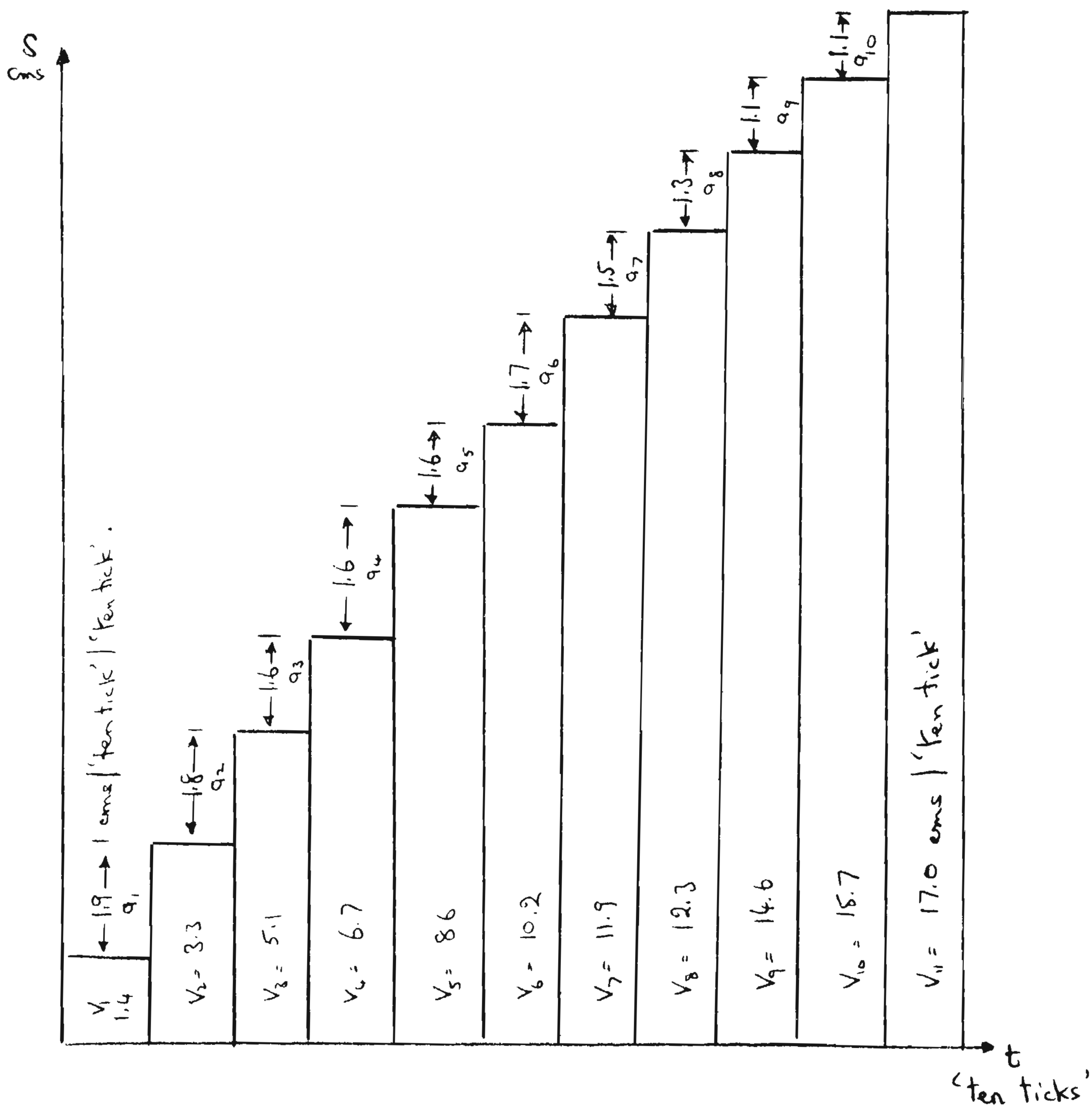
(iii) It is difficult to adjust the slope to compensate exactly for friction. The student can simply do his best. The following graph illustrates a typical student effort.



The initial acceleration of the cart under the effect of the rubber bands is clear. The subsequent motion shows a fairly constant velocity with some fall off due to friction.

2.22 Acceleration

(i) Students will see that the increase in velocity from interval to interval is fairly steady, although it falls off slowly with time in the example chosen for the graph. Let the students measure the increases in velocity for each interval, expressing the increase in cms per 'ten tick' (1.9) or cms per second (9.5) for each interval of time. This will help them understand the idea of acceleration.



Averaging the velocities of the cart over the first 5 intervals, by the two methods suggested, the following average velocities are obtained:

$$\bar{v} = \frac{v_1 + v_2 + v_3 + v_4 + v_5}{5}$$

$$= 5.0 \text{ cms/'ten tick'}$$

$$\bar{v}' = \frac{v_1 + v_5}{2}$$

$$= 5.0 \text{ cms/'ten tick'}$$

It will be noted that the velocity $\bar{v}''$ recorded for the middle interval is very close to the above two averages.

$$\bar{v}'' = 5.1 \text{ cms/'ten tick'}$$

If the results for all the intervals under consideration are tabulated it soon becomes clear that when the acceleration remains reasonably constant that the average velocity during a given number of intervals may be determined by any of the three methods considered above.

n	$\bar{v}$	$\bar{v}'$	$\bar{v}''$	Range of Acceleration
3	3.3	3.3	3.3	1.9 to 1.6
5	5.0	5.0	5.1	1.9 to 1.6
7	6.7	6.7	6.7	1.9 to 1.5
9	8.2	8.0	8.6	1.9 to 1.1

At this stage it is useful to get the students together to discuss their results, and to see what other information can be derived from the graph. Introduction of the equations of motion should follow naturally.

The determination of the velocity in each 'ten tick' interval of time 'T' has already been determined from the graph as follows,

$$v_1 = \frac{s_1}{T} \qquad v_2 = \frac{s_2}{T} \qquad v_3 = \frac{s_3}{T}$$

and the average velocity throughout 3 such intervals, where a total time 't' and total distance 's' elapses, has been shown to be given by:

$$\bar{v} = \frac{v_1 + v_2 + v_3}{3}$$

$$= \frac{s_1 + s_2 + s_3}{3T} \quad \text{so long as acceleration is constant}$$

$$\bar{v} = \frac{s}{t} \qquad \text{\_\_\_\_\_\_\_\_(1)}$$

Similarly, the acceleration for each interval has already been determined from the graph according to the following format:

$$a_1 = \frac{v_2 - v_1}{T} \qquad a_2 = \frac{v_3 - v_2}{T} \qquad a_3 = \frac{v_4 - v_2}{T}$$

Assuming that the acceleration remains constant 'a' throughout the full interval of time 't' it must follow that:

$$a = \frac{a_1 + a_2 + a_3}{3}$$

$$= \frac{(v_2 - v_1) + (v_3 - v_2) + (v_4 - v_3)}{3T}$$

$$a = \frac{v_4 - v_1}{t}$$

This may be expressed in more general terms as:

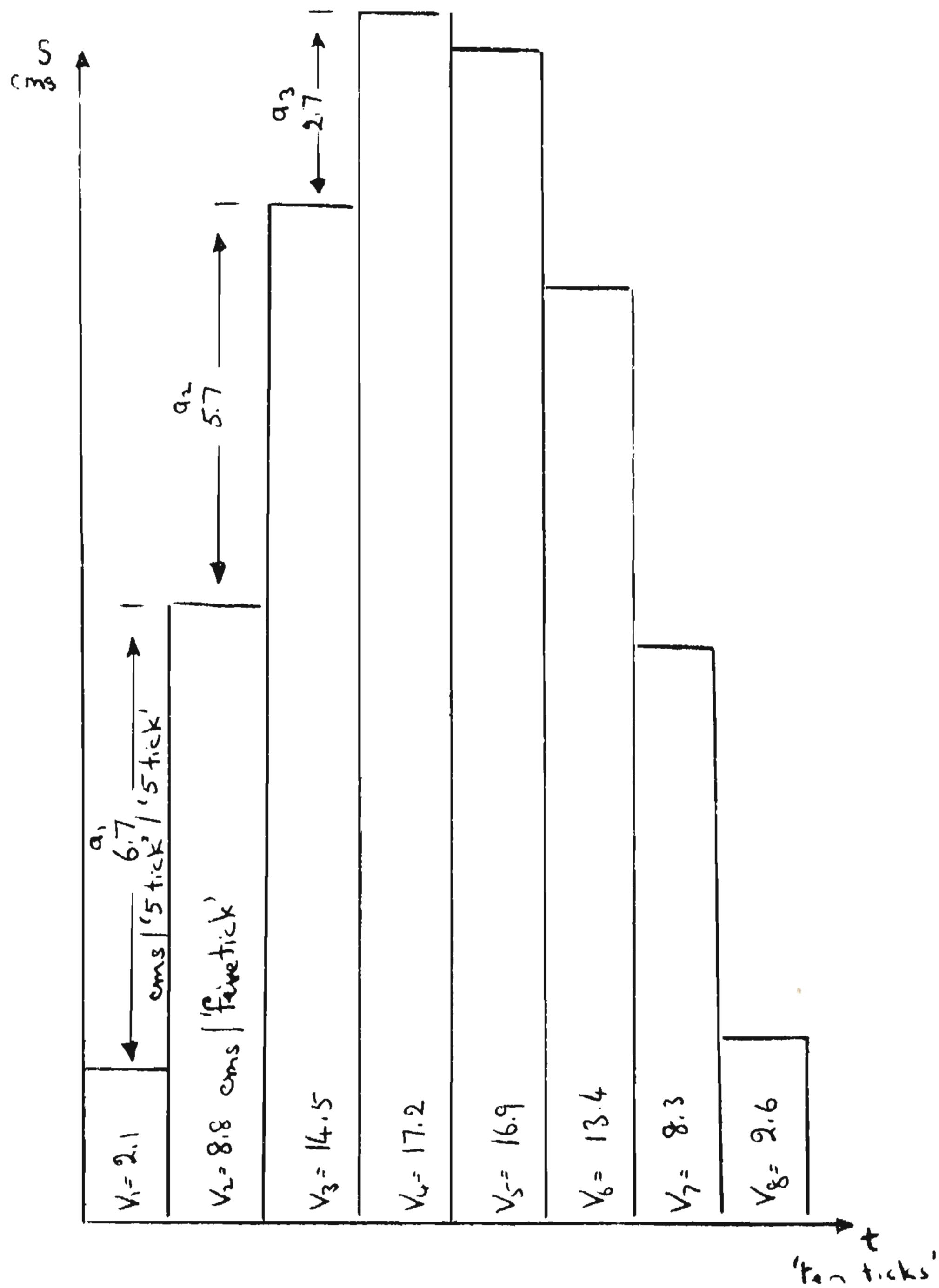
$$a = \frac{v_n - v_1}{t} \qquad \text{\_\_\_\_\_\_\_\_(2)}$$

The third equation has already been developed, and presented in the form:

$$\bar{v} = \frac{v_1 + v_n}{2} \qquad \text{\_\_\_\_\_\_\_\_(3)}$$

From the above 3 equations may be developed all the equations of motion.

(ii) The results of the pendulum experiment tabulated as before show clearly that the acceleration involved is not uniform. In fact it varies from positive (gain of velocity) to negative (loss of velocity).



Applying the three methods utilized in the foregoing activity to determine the average velocity for the first seven '5 tick' intervals the following results are obtained:

$$\bar{v} = \frac{v_1 + v_2 + v_3 + v_4 + v_5 + v_6 + v_7}{7}$$

$$= 11.6 \text{ cms/'5 tick'}$$

$$\bar{v}' = \frac{v_1 + v_7}{2}$$

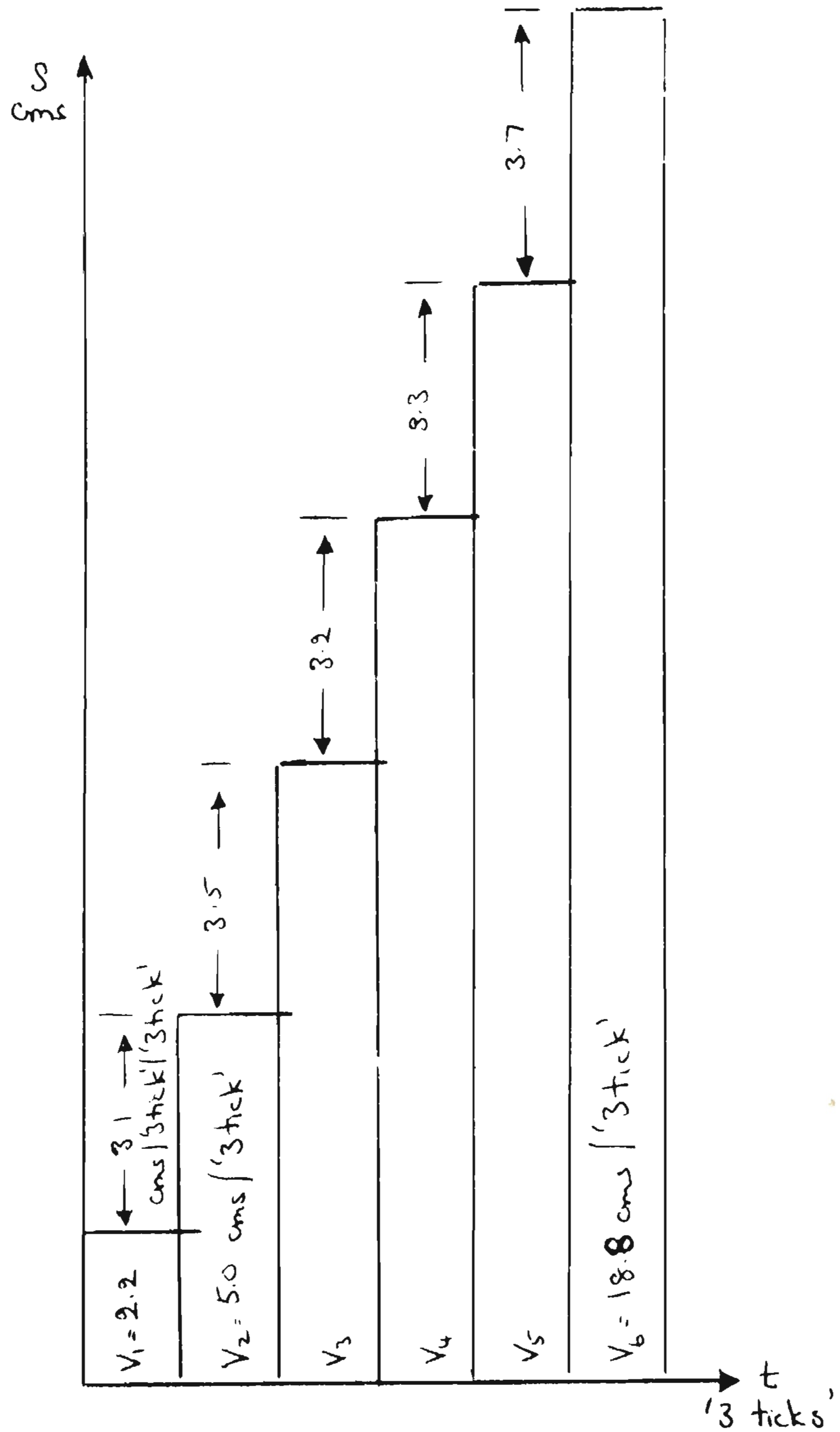
$$= 5.2 \text{ cms/'5 tick'}$$

$$\bar{v}'' = v_4$$

$$= 17.2 \text{ cms/'5 tick'}$$

It should be clear to the student that the simple equations developed in the first activity can only be applied to motions in which the acceleration remains constant throughout, and not to motions such as the above where the acceleration varies.

(iii) Gravitational fall reveals itself as a motion with uniform acceleration.



The average acceleration may be determined from the graph:

$$a = 3.3 \quad \text{cms/'3 tick'/'3 tick'}$$

$$= 3.3 \quad \text{cms}/\tfrac{3}{50}\ \text{secs}/\tfrac{3}{50}\ \text{secs}$$

$$= 3.3 \times \frac{50}{3} \quad \text{cms/sec}/\tfrac{3}{50}\ \text{sec}$$

$$= 3.3 \times \frac{50}{3} \times \frac{50}{3}\ \text{cms/sec/sec}$$

$$= 917 \quad \text{cms/sec}^2$$

It was found necessary to check the frequency of vibration of the timer immediately after the experiment for it was noted that the frequency would fall off as the voltage supplied fell. Thus after 5 or 6 experiments it was noted the frequency had fallen from 50 to 45 vibrations per sec.

If the student repeats the experiment with masses ranging from 100 gms to 1,000 gms he will find that friction has greater effect on the smaller mass, and that the acceleration is slightly affected.

(Acceleration due to gravity is generally accepted as being 981 cms/sec/sec. This value should give some indication of the limitations of this particular experiment).

(iv) It will be observed that the unfolded sheet of paper will drop much more slowly than the stone. The student will have little difficulty in suggesting that this is due to air friction, but he will not be sure that if friction is reduced the two bodies will fall at the same rate.

Folding the paper reduces the effect of air friction, and this becomes a minimum if the folded paper is dropped with its plane perpendicular to the Earth's surface. In this event the paper and stone when released simultaneously will hit the ground at the same instant. The indication is that, regardless of the mass involved, all bodies will drop to the Earth with the same rate of acceleration, so long as the effect of friction can be neglected.

2.30 FORCE AND MOTION

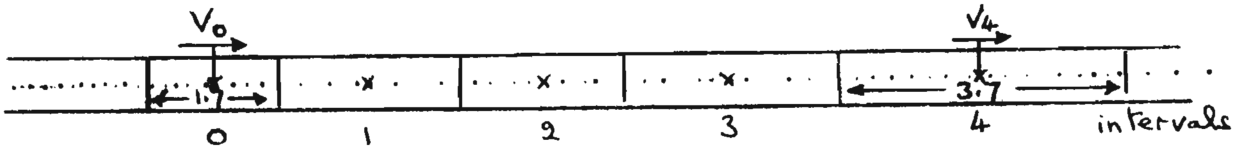
2.31 Force, Mass and Acceleration

(i) The loaded cylinder needs a much greater push than the unloaded cylinder to set it in motion, and the same is true of the loaded and unloaded cart. The greater the push exerted the greater the speed with which the cart or cylinder moves across the surface.

Encourage the student to think of everyday examples. Ask him whether it is easier to push a car or a truck. He will soon suggest that heavier bodies are more difficult to push. If he explains this behavior by saying that more friction is involved in the case of larger masses, do not contradict it. Suggest that he might investigate this more thoroughly in the following experiments where the effects of friction are compensated for. Ask him what type of motion he would expect if the same force is applied to different masses, if friction effects can be neglected. The following experiments will soon correct any erroneous ideas, and the investigation will be just as valid. The idea of this introduction is to get the student thinking for himself about the problems of force and motion. He will not discover anything new at this stage, but he might gain some incentive to investigate the problem more deeply.

If the student wishes to continue determining the acceleration of the cart by cutting up the ticker tape into 'ten tick' sections let him do so for a few of the readings. He will soon realize that the process is rather laborious and can probably be speeded up. When he begins asking whether it is necessary to always cut up the tape into 'ten tick' lengths help him to see how this can be avoided. He will soon recognize that all he needs to do is to mark off every 'ten tick' interval on the tape itself, and determine the acceleration from the velocities of the first and last intervals. Hence in the example below:

$$a = \frac{v_4 - v_o}{4} \quad \text{cms/'ten tick'/'ten tick'}$$



t = total time under consideration, i.e., 4 'ten tick' intervals

v_o = velocity at beginning of first interval = 1.7 cms/'ten tick'

v_4 = velocity at end of last interval = 3.7 cms/'ten tick'

The following results are typical of what might be obtained using 4 different forces on the cart.

F	a cms/t/t*
F_o	1.0
$2F_o$	1.9
$3F_o$	2.9
$4F_o$	3.9

*t = 'ten tick'

The student should not have too much difficulty in recognizing that if the force on the cart is increased n times to nF_o it would appear that the acceleration would also increase n times. In other words:

$$a \propto F \quad \text{(if m is constant)}$$

(iii) and (iv) The effect of friction on the cart tends to be greater when the total mass of the cart is less, and the angle of the compensating slope required must be increased accordingly.

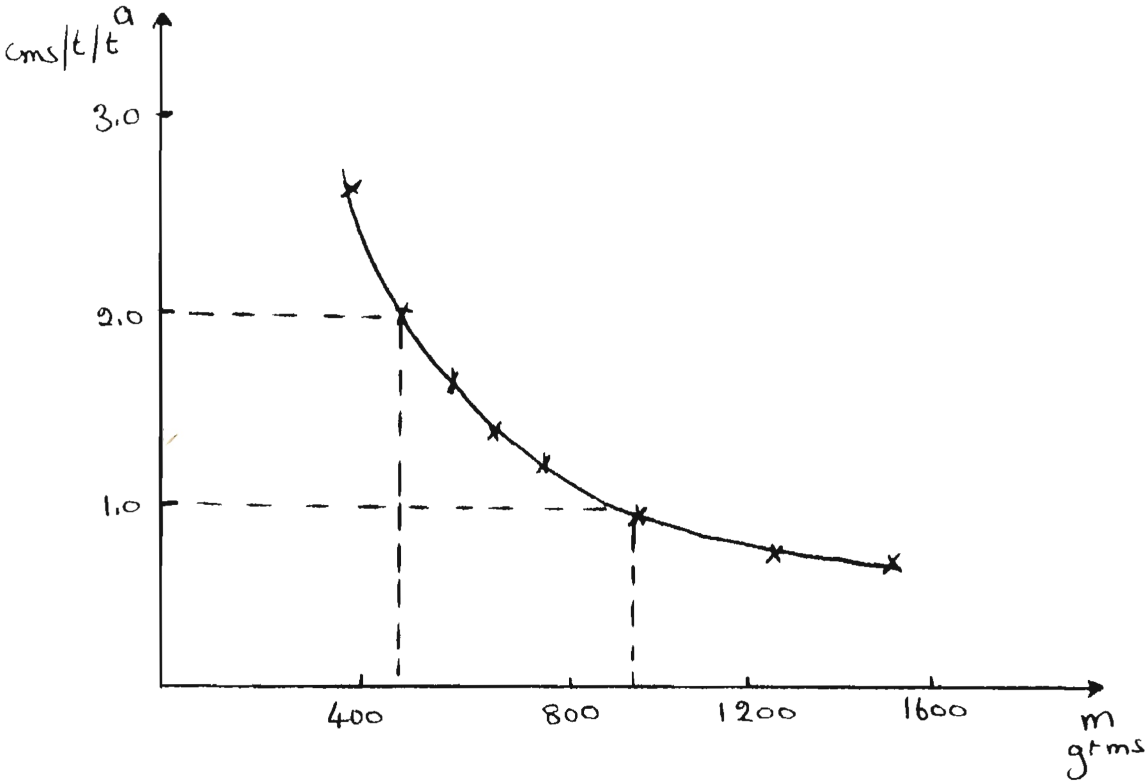
m	a cms/t/t
m_o	2.6
$2m_o$	1.3
$3m_o$	0.9
$4m_o$	0.7

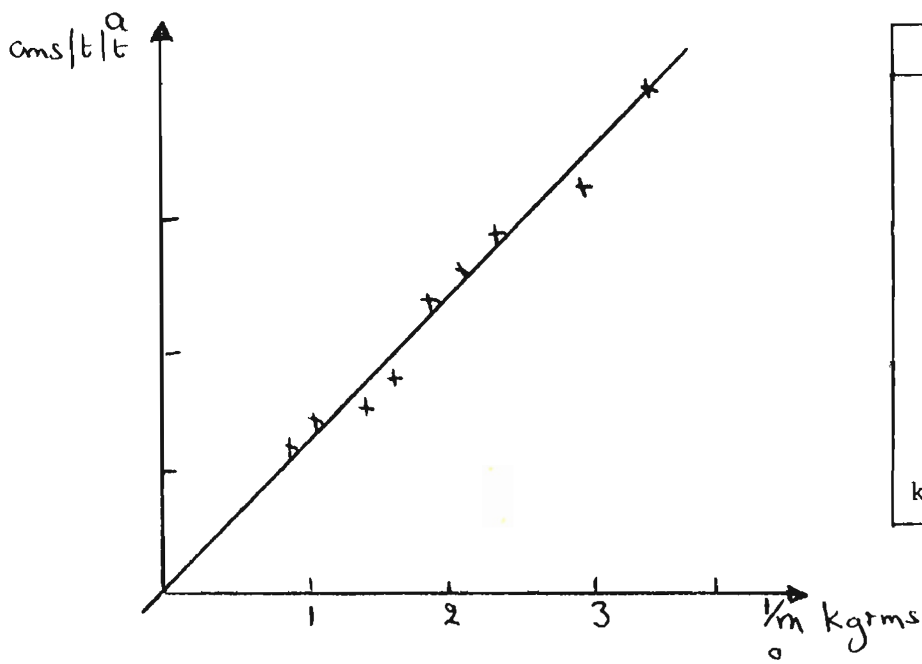
From the above results it is fairly clear that if the original mass of the cart m_o is doubled the acceleration is halved (2.6 to 1.3), and that if the mass is trebled the acceleration is divided by 3 (2.6 to 0.9), or in general

$$a \propto \frac{1}{m} \quad \text{(if F is constant)}$$

This is a good opportunity to convince the student of the value of graphs. His results may not be as good as those indicated above, but by taking more readings, and drawing a graph, he might be convinced that his results still conform to the suggested trend. Suggest that he draws a graph of 'a' against 'm' and then a graph of 'a' against $\frac{'1'}{m}$ for a more extensive set of readings such as those below. He will soon see why.

m gms	a cms/t/t
400	2.6
500	1.9
600	1.7
700	1.5
800	1.3
1,000	1.0
1,200	0.9
1,400	0.8
1,600	0.7





m	1/m	a
0.4	2.5	2.6
0.5	2.0	1.9
0.6	1.7	1.7
0.8	1.2	1.3
1.0	1.0	1.0
1.2	0.8	0.9
1.4	0.7	0.8
1.6	0.6	0.7
kgms	1/kgms	cms/t/t

In the above experiment the slope of the plane was set to compensate for friction affecting the motion of the unloaded cart. The slope was not changed during the experiment. A check at the end of the experiment indicated that the compensated slope required by the loaded cart was less than that required by the unloaded cart. In theory the slope should have been adjusted each time the mass of the cart was changed. In actual practice the failure to compensate the slope for every new mass produces only a small error, and it is not recommended that the experiment be made too laborious by doing this.

(v) Looking once more at the results of activity (ii) in which the loaded cart (1,000gms) was subjected to forces F_o, $2F_o$, $3F_o$ and $4F_o$ (1, 2, 3 and 4 elastic strands extended a fixed distance, in this case 10 cms) it is clear that, knowing the mass of the cart (1 kgm), and the acceleration produced, the force exerted by the chain of elastic bands can be calculated in each case from the relation F = ma.

m kgms	a cms/t/t or	cms/sec/sec	F nF_o or	Newtons (m.a)
1	1	0.25	F_o	0.25
1	2	0.50	$2F_o$	0.50
1	3	0.75	$3F_o$	0.75
1	4	1.00	$4F_o$	1.00

It follows that a chain of single rubber strands extended by 10 cms in this case exerts a force of 0.25 Newtons, while a chain of 4 parallel rubber strands extended by 10 cms exerts a force of 1 Newton. The balance may thus be calibrated in Newtons against the chains of extended rubber strands.

An interesting check for the student to make is to determine whether the chains of elastic strands undergo any permanent deformation when stretched by 10 cms. This can be done by hooking the end of a spring balance on to a chain and balancing the spring against a 10 cm extension of the chain. This might be repeated several times, and in all cases the extension of the spring is noted to be the same whenever the chain is stretched by 10 cms. The extension is in fact well within the elastic limits of behavior of the chain.

(vi) A 100 gm mass is pulled towards the Earth with a force of approximately 1 Newton since:

$$F = m.a \qquad \text{where } m = \frac{1}{10} \text{ kgm, } a = 9.81 \text{ meters/sec/sec}$$

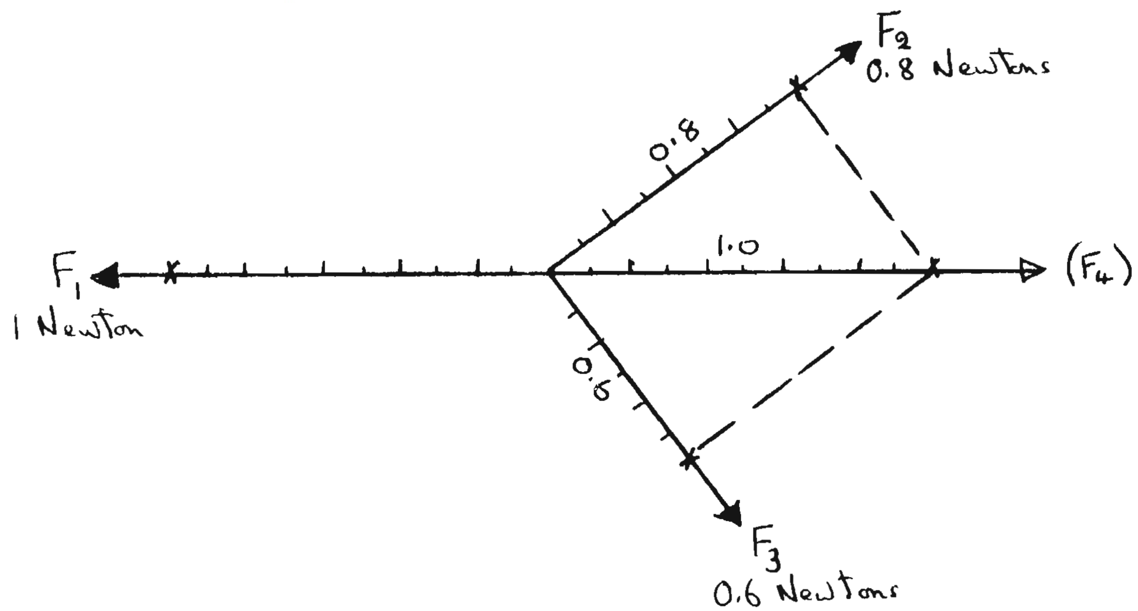
$$= \frac{1}{10} \times 9.81$$

$$= 0.98 \text{ Newtons}$$

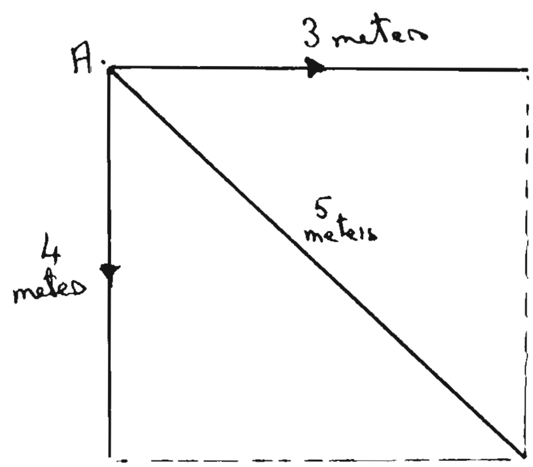
In fact the 100 gm mass produces effectively the same extension of the spring balance as the 4 extended elastic chains.

2.32 Addition of Forces

The student should be able to see from his results that, if two forces F_2 and F_3 are represented in magnitude and direction by the adjacent sides of a parallelogram, that they can be replaced by a single force (F_4) which is represented in magnitude and direction by the diagonal of the same parallelogram. There is no need for the student to be able to quote such a rule by heart. All that is required is an understanding of the principle involved.



It should be clear that F_1 does not equal the sum of F_2 and F_3. This is further clarified by the example of the boy and train in motion. The distances moved by the boy and the train in 1 second may be represented by the sides of a parallellogram in very much the same way as with the forces. The resultant distance moved by the boy relative to the ground is not 7 meters (3 + 4), but is that

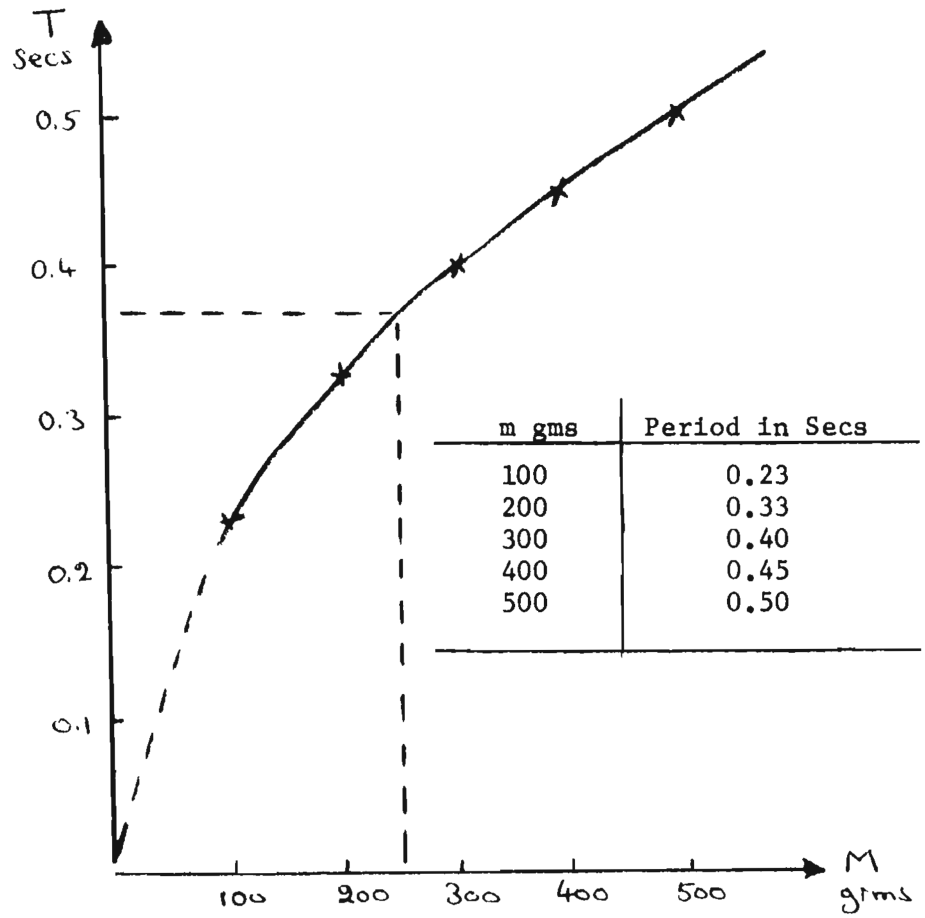


direction, and distance (5 meters), represented by the parallelogram of which the two motions form adjacent sides.

2.40 MASS

2.41 Mass and Inertia

(i) A typical set of results and the relevant graph is indicated below.



m gms	Period in Secs
100	0.23
200	0.33
300	0.40
400	0.45
500	0.50

It is sufficient for the student to realize that each mass has its own particular particular period of vibration. This should not be too surprising as it has already been seen that the greater the mass of a body the greater its inertia (or reluctance to be moved by a force). The greater the mass of the platform the greater its inertia, and hence the greater the time required for a complete oscillation. Placing the unknown mass on the balance the period was noted as being 0.375 secs. It therefore followed that the total platform mass was 250 gms, and that the actual body placed on the platform had a mass of 150 gms.

You might also ask your students to plot a graph of the mass (M) against the square of the period of oscillation (T^2). The result should approximate a straight line.

(ii) Varying the force of gravity on the mass on the platform should not affect the period of the vibrations. However, if the elastic is relatively short it will not only exert a vertical component of force on the mass throughout its motion, but also a horizontal component of force which will slightly affect the period. The results below were produced by such an effect.

FORCE ON MASS	PERIOD OF VIBRATION
Upward	0.475 secs
None	0.500
Downward	0.475

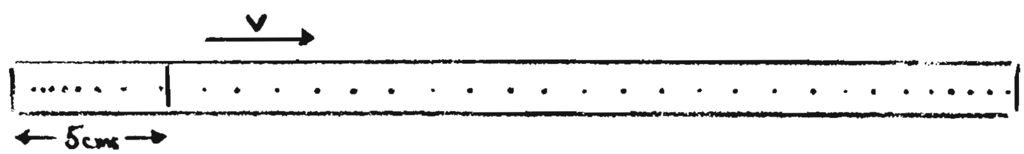
If the elastic chain could be held in the vertical throughout the motion, by following the motion of the platform, then the discrepancy would be eliminated. However, the simplest solution is to minimize the effect of the horizontal component of the force by using chains of rubber bands as long as is possible.

2.50 ACTION, REACTION AND MOMENTUM

It is our intention to study action and reaction by evolving simple theories, and then testing these out. It is important to stress that we are only theorizing, or guessing, and that our theories may be wrong, and that the purpose of the experiments is to test out the theories. It does no harm to even suggest to the student that although we discovered that action and reaction were equal and opposite when stationary bodies were involved we might expect the relationship to break down when moving bodies are involved. The student's discovery to the contrary will then be all the more exciting. Do not indicate before the experiments begin that you expect action and reaction to be equal and opposite, or momentum to be conserved. The student will then be surprised and excited to discover a simple law for himself which covers all types of collisions.

2.51 Direct Collisions between Carts

(i) After the carts have pushed each other apart, each tape will indicate a pattern similar to that in the diagram. If the length of the protruding spring on cart 1 is 10 cms, then each cart will be subject to an initial acceleration over a distance of 5 cms while the spring acts between the carts. The velocities will then remain fairly steady, falling off gradually due to friction. In measuring the velocities of the



carts on separation it is important to obtain a reading after the initial acceleration due to the spring has occurred, but before deceleration due to friction begins.

In a typical series of experiments the following results were obtained. The values computed for momentum have been corrected to the nearest significant figure.

m_1 gms	m_2 gms	v_1 cms/'5 tick'	v_2 cms/'5 tick'	m_1v_1 gm.cms/'5 tick'	m_2v_2 gm.cms/'5 tick'
400	400	14.8	15.2	5,900	6,100
400	800	15.0	7.5	6,000	6,000
400	1,200	17.8	6.0	7,100	7,200

The results suggest that the momentum generated in each cart after collision is equal and opposite (indicated by a negative sign).

$$m_1v_1 = -m_2v_2$$

and our theory indicates that this would only be true if the initial action and reaction were equal and opposite.

$$F_1 = -F_2$$

You should stress to the student that he has not PROVED anything. Simply his results indicate a particular form of behavior. More accurate experiments by prominent scientists confirm these suggestions. However, it is important not to put all deviations down to errors, although these are the most likely cause in this case, for careful observation of such peculiarities sometimes gives rise to new laws. In other words let the student generalize on his results with care. Tell him if more accurate experimentation tends to confirm his results, but point out how science develops, and that what we believe today might be better explained by more accurate observation tomorrow. This is the way of science, and it is this which we want the student to understand.

It is useful for the student to present his results in a slightly different form.

If:

$$m_1 v_1 = -m_2 v_2$$

Then:

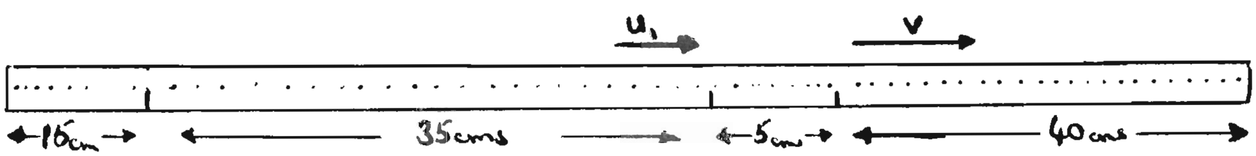
$$\frac{m_2}{m_1} = \frac{-v_1}{v_2}$$

Taking the results already obtained we can compare these quantities for the 3 experiments (correcting the ratio $\frac{v_1}{v_2}$ to the nearest significant figure).

$\frac{m_2}{m_1}$	$\frac{v_1}{v_2}$
1	1.0
2	2.0
3	3.0

(ii) If the table shows any indication of a slope (a fraction of a degree from the horizontal will show up on the ticker tape motion), it is preferable to run the carts down the slope, as this will to some extent compensate for friction. The initial velocity of cart 1 should be fairly high, for if the velocity after collision is too low frictional deceleration will be very obvious.

In an experiment in the laboratory two carts were placed 50 cms apart. Cart 1 was accelerated by stretching a chain of rubber bands by 15 cms. The resultant ticker tape marking was similar to that below. The first 15 cms indicated the acceleration of the cart and the next 35 cms a fairly steady velocity (slight fall off due to friction) prior to collision. The next



5 cms indicated the rapid deceleration of cart 1 as the needle penetrated the cork on cart 2, and the remainder of the tape, 40 cms, showed the

velocity of carts 1 and 2 together (slowing down under the effect of friction). The velocities 'u_1' and 'v' were recorded by measurements just before and just after the 5 cm central section. A typical set of results is given below.

m_1 gms	m_2 gms	u_1 cms/'5 tick'	v cms/'5 tick'	$(m_1 + m_2)v$ gm.cms/'5 tick'	m_1u_1 gm.cms/'5 tick'
400	400	18.7	9.1	7,300	7,500
800	400	17.5	10.8	13,000 (approx.)	14,000 (approx.)

Once again the results suggest that total momentum of the carts before collision equals the total momentum of the carts after collision, and this can only be true if action and reaction are equal and opposite during the collision itself.

It is probably more convincing for the student to rearrange the equation he has under scrutiny.

$$(m_1 + m_2)v = m_1u_1$$

$$\text{or } \frac{(m_1 + m_2)}{m_1} = \frac{u_1}{v}$$

If the equation is true the ratios of the masses and velocities should be approximately the same. Taking the same results as before the following ratios are obtained.

$\frac{m_1 + m_2}{m_1}$	$\frac{u_1}{v}$
2	2.0
1.5	1.6

2.52 Direct and Indirect Collisions between Ball Bearings

(i) It is recommended that the teacher should perform this activity with student assistance. In this way students are able to listen for the sound of balls striking the ground without the confusion of similar experiments adjacent to them.

As the velocity 'v' of the ball rolling off the table increases, the distance 'x' the ball travels horizontally in flight also increases. Some students may think that if the ball travels further in its horizontal flight the time of flight will also be greater. This is clarified when two balls are knocked off the table simultaneously. Regardless of the different flight paths both balls strike the ground simultaneously. Any teacher who can use a meter rule like a billiard cue will find this most useful, for a very convenient way of making both balls leave the table top simultaneously at different velocities is to create a glancing collision between the two ball bearings at the edge of the table.

It is now useful to show your students how you can determine the velocity 'v' of a ball as it leaves the table top simply by measuring the height 'y' of the table above the floor, and the horizontal distance 'x' travelled by the ball before it stikes the table, simply by substituting in the equation below:

$$v = x\sqrt{\frac{g}{2y}}$$

It is up to the individual teacher to determine how important the derivation is for his particular students. The equation is derived below.

In 2.22 the following equations of motion were developed:

$$\bar{v} = \frac{s}{t} \qquad \text{———— } (1)$$

$$a = \frac{v_2 - v_1}{t} \qquad \text{———— } (2)$$

$$\bar{v} = \frac{v_1 + v_2}{t} \qquad \text{———— } (3)$$

It therefore follows from (1) that:

$$s = \bar{v}t$$

Substituting for $\bar{v}$ from (3) we obtain:

$$s = \frac{[v_1 + v_2]t}{2}$$

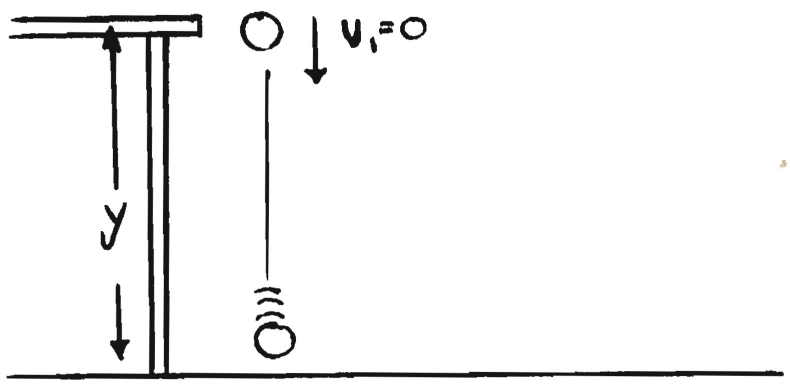
Obtaining a value for v_2 from equation (2) this becomes:

$$s = \frac{[v_1 + (v_1 + at)]t}{2}$$

$$\text{or} \quad s = v_1 + 1/2at^2 \qquad \text{———— } (4)$$

This is another form of our equations of motion.

Now apply the above equation to the case of a ball bearing sitting on the edge of a table which is given a small push and drops to the floor. At the beginning of the motion its velocity is zero (v_1 = o). The ball then accelerates under the pull of gravity at a rate of 9.81 meters/sec/sec ($a = g$) as it falls to the floor ($s = y$).



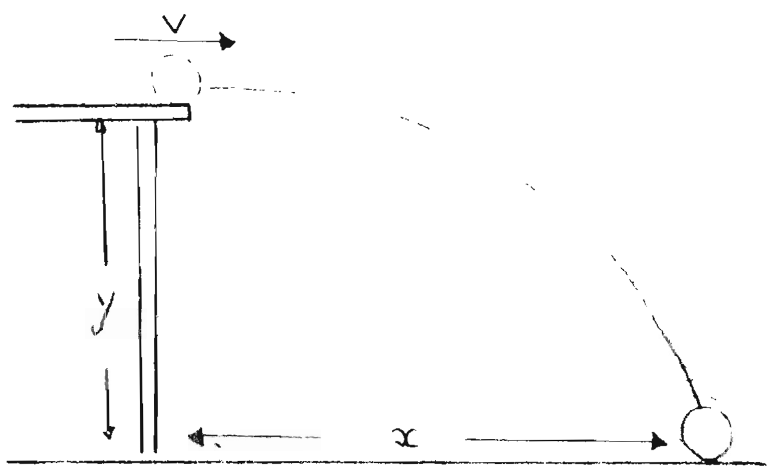
Substituting the specific values in equation (4) it follows that:

$$y = o + 1/2gt^2$$

$$\text{or} \quad t = \sqrt{\frac{2y}{g}}$$

This is the time required for any ball to drop to the floor from the same table top regardless of the distance it travels through the air. This is because the only force acting on the ball is that of gravity which acts vertically downwards. A projected body thus has a constant vertical acceleration towards the Earth while its horizontal velocity 'v' remains constant.

Now consider a ball bearing leaving the table top with an initial horizontal velocity 'v'. We now know that it will take 't' seconds to hit the



floor, and that during that time the horizontal component 'v' of its velocity will remain constant. The horizontal distance 'x' travelled across the floor will thus be given by the equation:

$$x = vt$$

where we already know that:

$$t = \sqrt{\frac{2y}{g}}$$

Substituting in the first equation for 't' it follows that:

$$x = v\sqrt{\frac{2y}{g}}$$

$$\text{or} \quad \boxed{v = x\sqrt{\frac{g}{2y}}}$$

(ii) The results indicated below were obtained by performing the experiment first of all with ball bearings, 1.2 cms in diameter, and then with ball bearings 2.4 cms in diameter. The latter produced the better results, possibly due to the fact that the effect of friction is less with heavier balls.

	Small Ball Bearings	Large Ball Bearings
x_1	0.0 ± 0.2	0.0 ± 0.3
x_2	34.5 ± 0.5	40.6 ± 0.2
$x_1 + x_2$	34.5 ± 0.7	40.6 ± 0.5
x_o	35.9 ± 0.5	40.7 ± 0.3

In both cases the results support the relationship:

$$x_o = x_1 + x_2$$

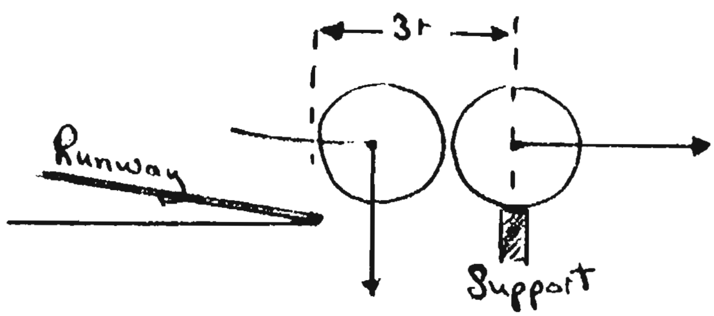
and hence support the hypothesis that during the collision action equals reaction:

$$F_1 = -F_2$$

or that momentum is conserved:

$$mu_1 = mv_1 + mv_2$$

The student will probably be intrigued to find that after impact the first ball has no horizontal velocity, and simply drops vertically downwards. This will of course explain to him the reason for setting the ball bearing support at a distance of '3r' from the end of the runway, thus permitting just sufficient space for the ball bearing to drop vertically downwards between the runway and support.

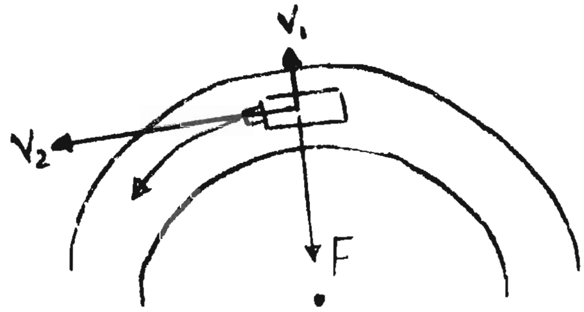


2.60 CIRCULAR MOTION

2.61 Centripetal Force

(i) The evidence of the motion of the Moon and Planets suggest that circular orbits are a natural form of motion in the Universe.

At first glance the motion of loose packages on the top of the bus appears to contradict this idea. Moving round a sharp corner the packages would show a tendency to slide off the roof (v_1) at right angles to the

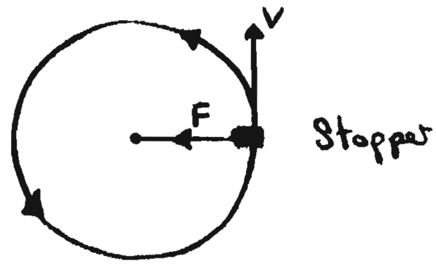


direction of motion, suggesting the need to pull the packages back into position with a force (F) directed towards the center of the circle, of which the road is a section. If the bus braked suddenly the packages would fly forward (v_2) in a straight line, rather than along a curved one. The evidence tends to suggest that circular motion is not as natural as one might at first anticipate.

(ii) The student will have no difficulty in feeling the pull of the string on his finger. However, get him to discuss what his finger is doing, that is, applying a force to the string. Discuss how the force is transmitted through the string to the rotating stopper. If this force is removed circular motion is no longer possible. This is best demonstrated (by you) in the open. Simply remove your finger from the string, and let the students watch the motion of the stopper as it flies off at a tangent following the more natural state of motion which is a straight line (v).

Emphasize that in order to obtain circular motion a central force 'F' (centripetal force) is required to act on the rotating body. Compare the motion of satellites around the Earth, the Moon around the Earth, and Planets around the Sun, with that of the stopper about the glass tube. Get the student

to suggest that such rotating bodies must be acted upon by a centripetal force in order to continue along a circular path.



Be a little more specific and discuss the centripetal force exerted on a satellite by the Earth. Clearly a force must act on the satellite towards the Earth if it is to continue following a circular orbit. Ask students if they can think of any other similar forces directed towards the center of the Earth. They should recall how bodies fall under the effect of gravity towards the center of the Earth. If the Earth exerts a force on small bodies it is not too surprising to find that it exerts a force on much larger bodies such as satellites or the Moon, and it is this force which acts as a centripetal force making orbital motion possible.

This series of observations is very crude, but very effective.

The first indicates that if the mass of the rotating body, and its radius of motion, remain constant the centripetal force exerted increases as the rate of rotation increases.

The second indicates that for a given rate of motion, with a fixed radius, the force involved is reduced by reducing the mass of the rotating body. In this particular instance, the centripetal force exerted on the paper clip, even at high rotating speeds, is less than that exerted on the rubber stopper at very slow rates of rotation.

Finally, it is noted that increasing the radius of motion, while the rate of rotation and the mass of the rotating body remain constant, increases the centripetal force required to maintain the motion in a circular path.

(iv) This experiment is probably best performed with 3 students. One might rotate the stopper carefully noting the force exerted by the spring balance. A second might count the oscillations of the stopper, while a third might watch a simple pendulum to indicate to the group when to begin counting the rotations and when to stop. Each experiment should be repeated 3 times over to obtain an average value for the number of revolutions per minute, and to give some indication of the error involved. The following is a typical set of results:

F Newtons	n revs/min
0.05 ± 0.01	90 ± 10
0.10	120
0.15	140
0.20	170

It is noted that F increases as n increases. This immediately excludes an inverse relationship such as:

$$F \propto \frac{1}{n} \quad \text{or} \quad F \propto \frac{1}{n^2}$$

It is therefore of interest to make tables comparing the force 'F' with 'n' and also 'n^2'.

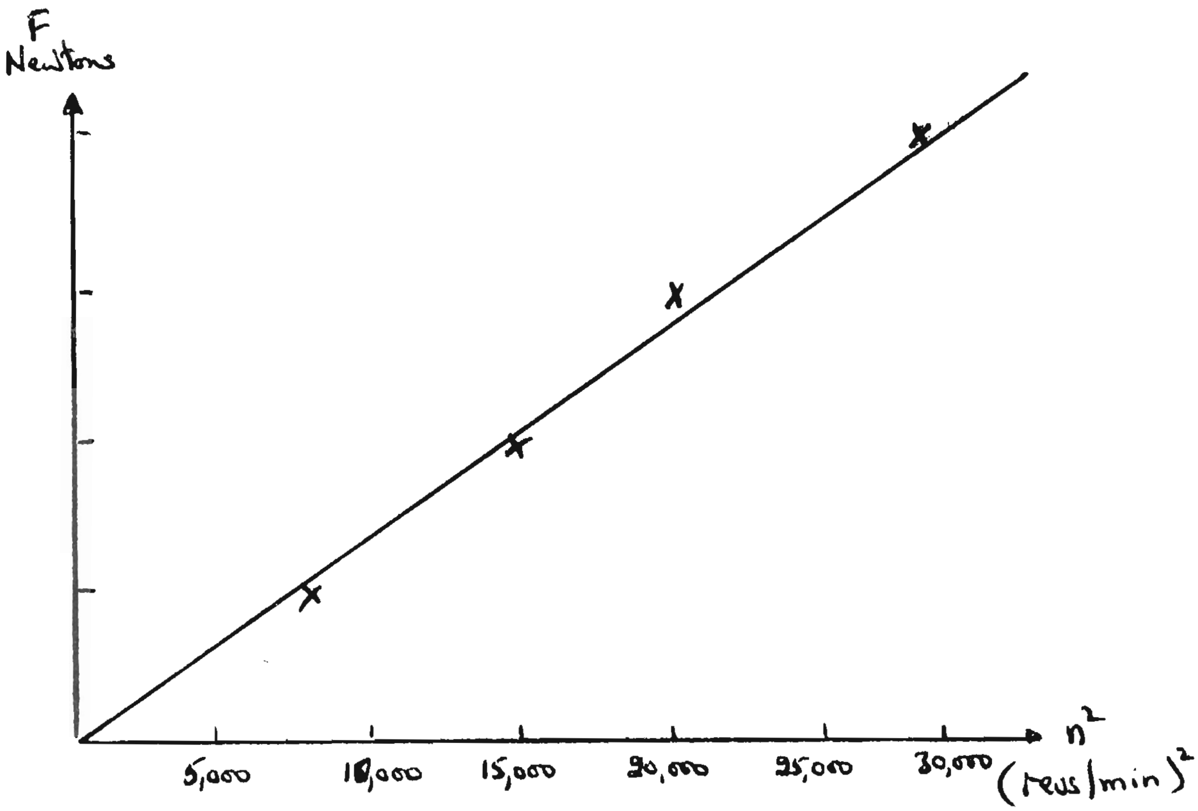
F Newtons	n revs/min	n^2
0.05	90	8,100
0.10	120	14,400
0.15	140	19,600
0.20	170	28,900

Multiplying the value of 'F' by 2 does not increase the value of 'n' by 2, but that of 'n^2'. The experiment does not prove that:

$$F \propto n^2$$

but it does suggest this as the most likely relationship of those proposed. Subsequent experimentation might well suggest a more subtle relationship.

Good students may be interested in plotting a graph of 'F' against 'n^2'. Normally 4 points (5 if we count zero) are insufficient for a graph, if any basic relationship is to be predicted. In this case the relationship has already been proposed, and the graph is suggested out of interest to see how the results conform to the predicted relationship. The graph is much more convincing than a simple scrutiny of the results alone.



A similar investigation could be conducted to determine a relationship between the centripetal force 'F' and the mass 'm' of the stopper when the radius 'r' of motion and the rate of revolutions 'n' are kept constant. It would be found that:

$$F \propto m$$

Another investigation could be conducted to determine a relationship between the centripetal force 'F' and the radius of rotation 'r' when the mass 'm' of the stopper and the rate of revolutions 'n' are kept constant. It would be found that:

$$F \propto r$$

Combining the results of 3 such experiments together it would be logical to indicate that:

$$F \propto mn^2r$$

$$\text{or} \quad F = (\text{Constant})\, mn^2r$$

Subsequent investigation would indicate the constant to have a value of $(2\pi)^2$ such that:

$$F = m(2\pi n)^2 r$$

In conclusion, it has been observed that a body subjected to a centripetal force must undergo acceleration in the direction of the centripetal force. The nature of this acceleration becomes clearer when it is realized that a body may follow a circular path with a constant speed, but not a constant velocity. Velocity is a vector quantity involving not only magnitude but also direction, and in circular motion the direction of the velocity changes continuously. The change is in fact created by the centripetal force which creates a change in a component of the velocity in the direction of the centripetal force.

2.70 WORK AND ENERGY

2.71 Energy Transfer

(i) The energy of motion comes from the initial position of the boy high on the hill. He may have used up his "food energy" in climbing the hill, but in the process he gained "hill energy". In skiing down the hill, the "hill energy" provided him with "motion energy".

The "motion energy" of the falling boy is taken up by the extended trampolene as "spring energy", which then throws the boy back into the air giving him back first "motion energy" and then "hill energy".

The idea of this introduction is to get the student to see energy as something which is transferred from one form to another, and not as some nebulous quantity which is created in a power station.

(ii) The lead becomes distinctly warm as it is flattened. It follows that at least some of the "motion energy" is converted into "heat energy". Similarly, the nail, close to the cut edge, becomes quite hot, indicating that some of the "motion energy" is converted to "heat energy".

It is important to recognize that whenever energy is converted from one form to another, heat is almost always created. As such it is rarely in a usable form and is lost energy. It is such loss of energy which makes machines so often inefficient.

(iii) With the help of the dynamo "bodily energy", which becomes "motion energy", is converted to "light energy" in the bulb. As soon as the bulb lights up it becomes more difficult to turn the dynamo handle. In other words more "bodily energy" is required to produce the new "light energy".

2.72 Measurement of Energy and Power

(i) Student A weighed 70 kgms. He found a flight of 20 steps, each 20 cms high, making the total flight 400 cms (or 4 meters). The work done by student A in climbing the stairs would be:

$$W = 70g \times 4$$
$$= 280g \text{ Joules}$$

Student B weighed 90 kgms, and it follows that he did much more work in climbing the same steps.

$$W = 90g \times 4$$
$$= 360g \text{ Joules}$$

(ii) Students A and B raced up the steps as fast as they could go, taking 4.0 and 3.5 seconds respectively. Their rates of climbing were therefore:

$$\text{Rate of Work of Student A} = \frac{280g}{4} \text{ Joules/sec}$$
$$= 686.7 \text{ Watts}$$
$$= \frac{686.7}{746} \text{ Horse Power}$$
$$= 0.92 \text{ Horse Power}$$

$$\text{Rate of Work of Student B} = \frac{360g}{3.5} = \text{Joules/sec}$$
$$= 1009 \text{ Watts}$$
$$= \frac{1009}{746} \text{ Horse Power}$$
$$= 1.35 \text{ Horse Power}$$

It is interesting for the students to realize that student B placed much more strain on his body than student A during the climb, not just because he ran up the stairs somewhat faster than A, but because he was so much heavier than student A.

2.73 Efficiency

(i) Using the simple machine it was noted that the spring balance must be moved through 60 cms in order to raise the mass 'm' through 30 cms. The forces exerted on the spring balance to lift the mass by means of the machine are recorded below for a typical experiment.

No. of Wheels Jammed	OUTPUT Joules	F Newtons	S Meters	INPUT Joules	EFFICIENCY
3	0.29	1.00	0.6	0.60	0.48
2	0.29	0.80	0.6	0.48	0.60
1	0.29	0.65	0.6	0.39	0.74
0	0.29	0.5	0.6	0.30	0.97

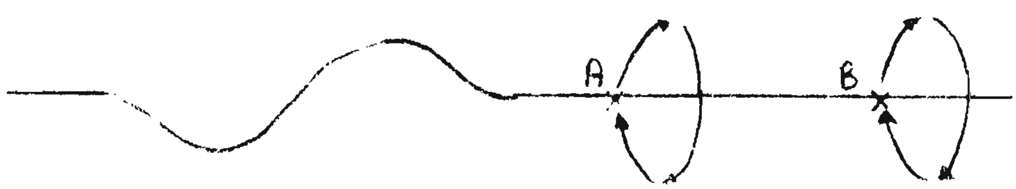
The efficiency of the machine clearly increases (0.48 to 0.97) as the friction is reduced (3 wheels jammed to 1 wheel jammed), and it would appear that if friction could be eliminated altogether the efficiency would increase to its maximum value of 1.00 (or expressed as a percentage 100%).

3. WAVE MOTION

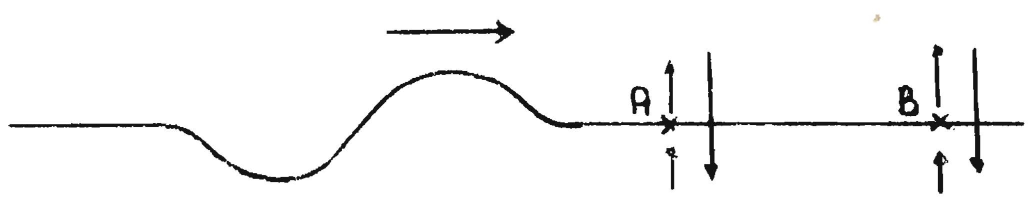
The idea of this introduction is to start the student thinking about waves and what they do. If you can arouse his curiosity the rest will follow easily.

When waves approach the shore they must change their direction otherwise we would notice them approaching at all sorts of strange angles, whereas in reality the line of the wave crests is always roughly parallel to the shore line. Don't explain why this happens to the student otherwise it will spoil the fun later, but by all means let him guess if he wants. He will be able to test out his ideas later by experiment.

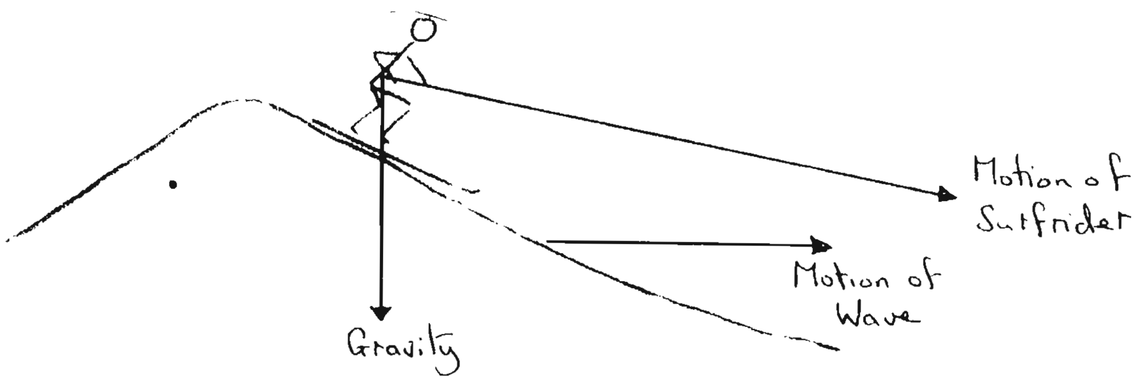
Although waves move forward there is no real forward movement of water. Observers sitting in boats at points A and B in the path of an oncoming wave would be displaced vertically by the motion, but would not move forward with the wave. The wave in fact carries displacement energy with it, and the time for this energy to be carried from A to B is the same as the



time for the wave crest to move over the same distance. In reality the displacement is not so much a straight vertical motion but a circular or elliptical motion. This explains the short forward and backward motion that is felt in a boat or noted on the sea shore.



Many students must at sometime have tried to push floating objects from one side of a pond to another by creating waves by hand or by throwing stones. It is always a most disillusioning process which simply confirms that the forward motion of the waves is not a forward motion of water. Having studied the whole topic of waves it may well be that students will feel unhappy about the anomaly of the surfrider. This is a good question to set them thinking for it appears to contradict the idea that water does not move forward. Here in fact the surfrider simply slides gradually down the slope of the wavefront (as it moves forward) taking advantage of the pull of gravity, and the fact that very little friction exists between the surfboard and the water. Once again the student should attempt to solve this problem for himself in the light of his experimental observations, although in this particular case he may well need fairly strong guidance.

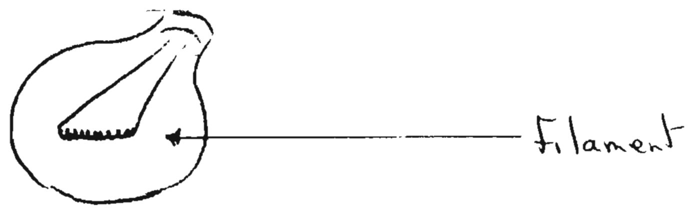


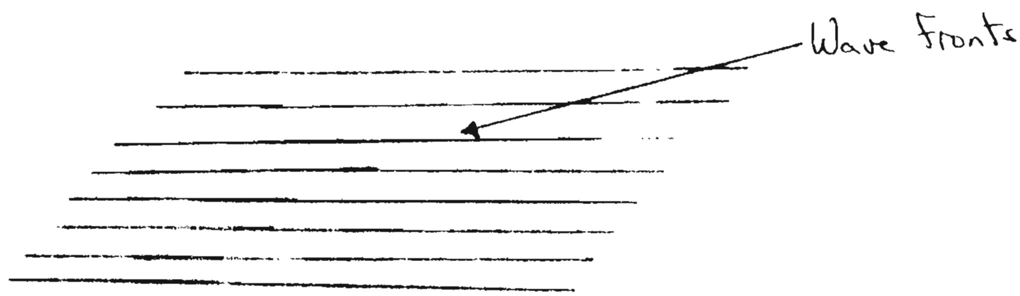
Arousing the student's curiosity with such problems will help generate his interest in the study of the ensuing phenomena.

3.10 NATURE OF WAVE MOTION

3.11 Waves and Pulses

(i) The wave crests act like lenses in focusing the light into images on the paper beneath the tank. Images may be formed with ordinary daylight, but the brightness and sharpness of the images is increased considerably by using an electrical light source. To obtain the brightest images the lamp filament should be parallel to the wavefronts being generated. The best height of the filament above the water will be approximately 50 cms.

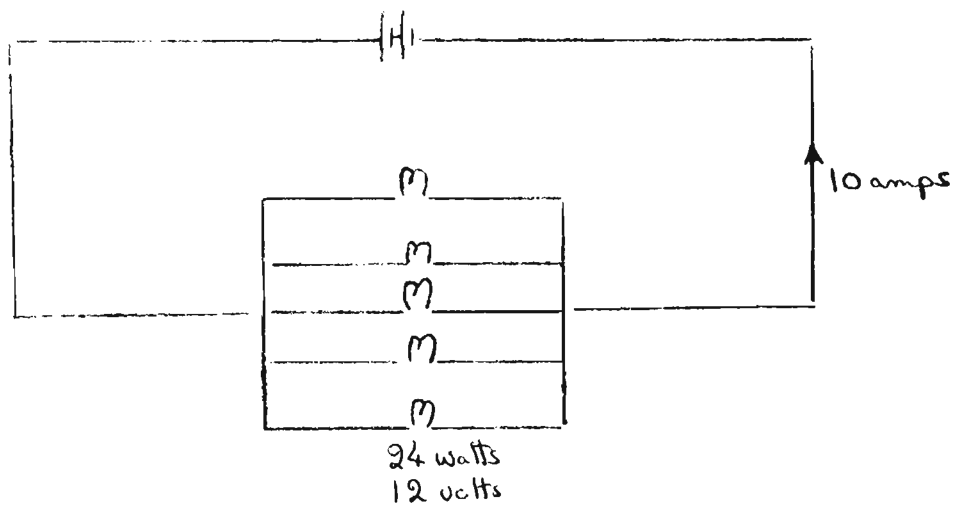




Give the students a word of warning. The ripple tank light operates on mains electricity (220 volts in many countries). This can be dangerous, particularly with water around. Suggest that one of the students in each group keeps his hands dry, and that he should be the one to switch the lamp on and off. Keep a careful check on switches, wires and fittings. Make sure that faulty fittings are rectified immediately, and that wires are not allowed to trail around in dangerous positions where students can trip over them. Clearly table top electrical outlets are the safest and most convenient for student use.

If mains electricity does not exist the ripple tank light housing may be redesigned to take a car bulb (say 12 volts, 24 watts), and a battery may be used to supply the current. However, the light emitted by the bulb would be limited and it would be necessary to at least partially darken the laboratory in order to see the images beneath the tank clearly.

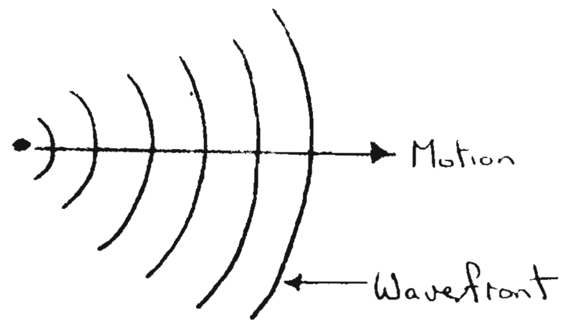
Several ripple tank bulbs might be operated by a single battery, the number being dependent on the battery rating. For example, a 12 volt battery might have a rating of 45 ampere hours over a 20 hour period. This means that it is capable of running at a steady rate of 2.25 amperes for 20 hours (20 x 2.25). Equally well it may be able to run at a steady 9 amperes for a shorter period of 5 hours, and even up to 40 to 50 amperes for very limited periods. However, the supplier will normally indicate a maximum rate of steady discharge of say 10 amperes.



If the car bulbs utilized are rated at 24 watts and 12 volts (ratings of bulbs are usually 6 to 12 volts for side lights, etc.) each bulb would draw 2 amps from the battery, and under the above conditions it would be unwise to have more than 5 ripple tanks simultaneously illuminated, as these would draw a steady 10 amps from the battery. If students are advised to switch off the lights as much as possible the strain on the battery would be considerably reduced, and even more lights might operate from the same battery. However, it would be better to get a second battery for additional ripple tanks.

Experiments using the sun as a source of light can provide surprisingly good results, but for obvious reasons it is difficult to recommend this as a normal means of illuminating the ripple tank.

In making observations with the ripple tank the student should have no difficulty in observing the patterns on the water surface as well as the images beneath the tank, and should note that the only difference between them is that the lower image pattern is a magnified, brightly illuminated version, of the actual pattern on the water surface.



If any point on a wavefront is observed it will be seen that its direction of motion is always at right angles to the wavefront produced.

Holding a pencil in contact with the water's surface is interesting since any movement of the hand is transmitted through the pencil to the water's surface. The creation of waves around the pencil indicates that the hand is vibrating, and not perfectly steady as many students would initially believe. This is an interesting lesson to learn at an early stage.

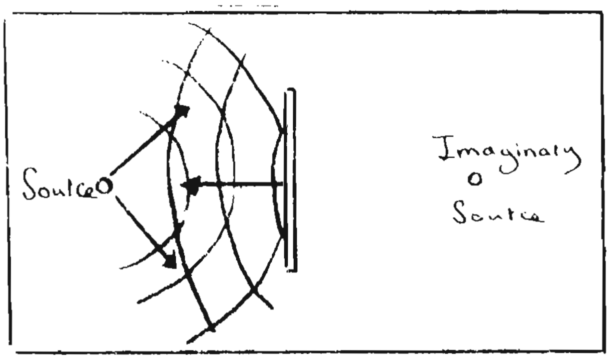
(ii) The fact that wavefronts are circular indicates not only that disturbances move out from a source in all directions, but also that the velocity of motion is equal in all directions. In this particular instance the motion is in two dimensions (on the water surface only).

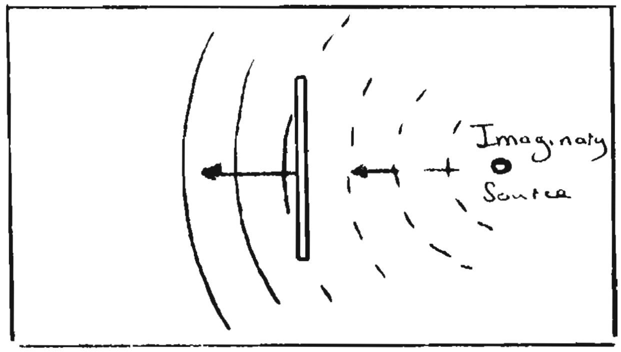
The fact that wavefronts do not carry the cork forward tend to illustrate the point already discussed, that water is not actually moving forward, but rather a displacement of water. Students may be able to see the very small displacement of the cork as the wavefront passes by. A simple discussion relating these observations to waves created in the sea should translate the experiment to a larger scale. With a little encouragement

the students should be able to suggest that what is moving forward is a vertical disturbance, and that this corresponds to a transfer of energy, for if the source was to vibrate continuously the cork would also vibrate continuously, and the only way in which it obtains its energy of vibration is through the wave motion.

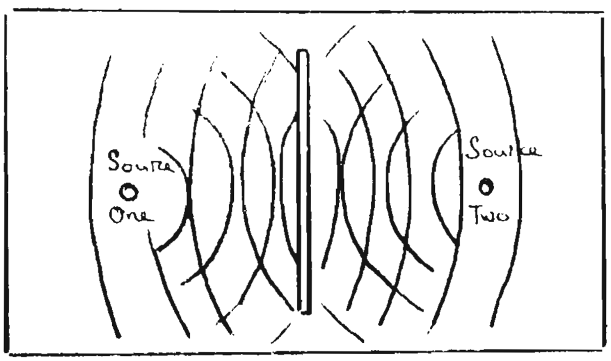
3.12 Reflection and Refraction

(i) The reflection from a straight barrier occurs in such a way as to make it appear as though the reflected wave originated from a point on the opposite side of the barrier which we might term the imaginary source. The position of the imaginary source is exactly as far behind the barrier as the real source is in front of it.

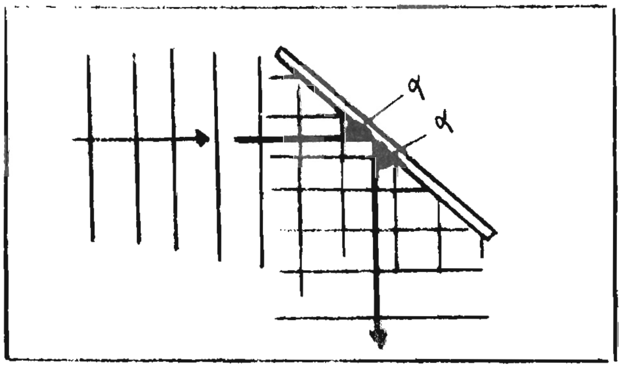


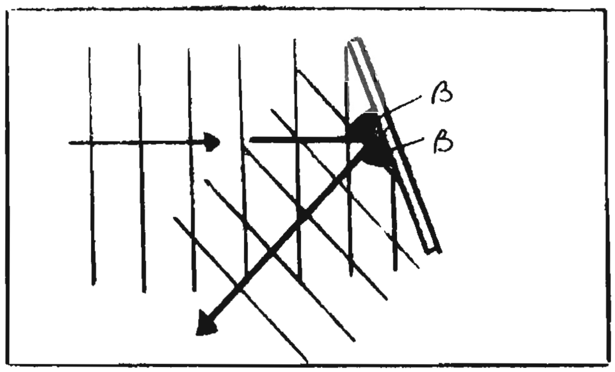


This becomes particularly clear when waves are generated from two positions either side of, and equal distances from, the barrier. It then appears as though the wave generated from the position of the imaginary source passes straight through the barrier, whereas in reality it is the simple fact that the reflected wave moves away from the barrier just as though it had originated from that point. Many students will be fascinated by this behavior whereby physics performs a magic trick. Let them enjoy the moment. We wish physics to be an enjoyable experience.



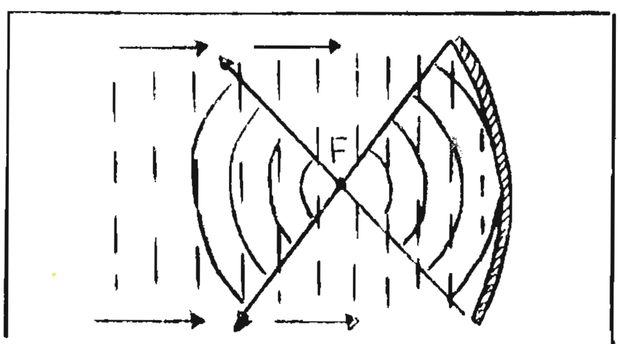
(ii) If the student is encouraged to note the direction of motion of the incident and reflected wavefronts relative to the barrier, possibly holding pieces of string to mark out the two directions of motion, he will find it easier to discover for himself that the reflected wavefront always moves away from the barrier at the same angle as that at which the incident wave approaches it.



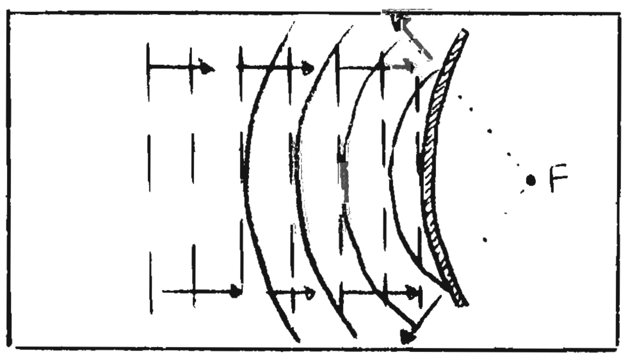


If the student has any difficulty in finding this out for himself encourage him to draw pictures of the wavefronts, even sketching these on a piece of paper beneath the tank, if necessary, in order to obtain the correct positions of the wavefronts. Get him to draw in the directions of motion of the wavefronts. Persuade him to repeat this with several barrier positions guessing the direction of the reflected wave, and then ask him why he guesses a certain direction.

(iii) Plane waves (that is waves with straight wavefronts) are reflected by a concave barrier to a focal point (F) into which the waves appear to concentrate, before spreading out once again. In the case of a convex barrier the waves spread out on reflection as though they are being generated from an imaginary focal point (F).

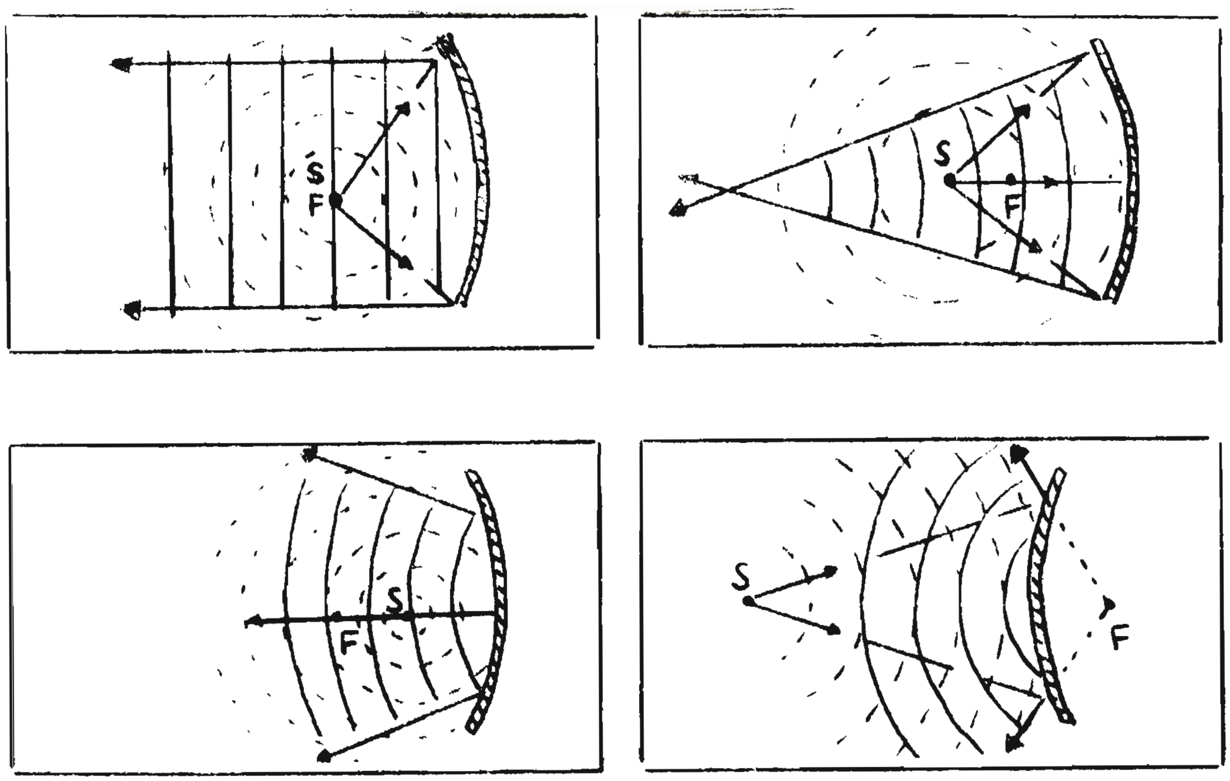


Reflection at Concave Barrier

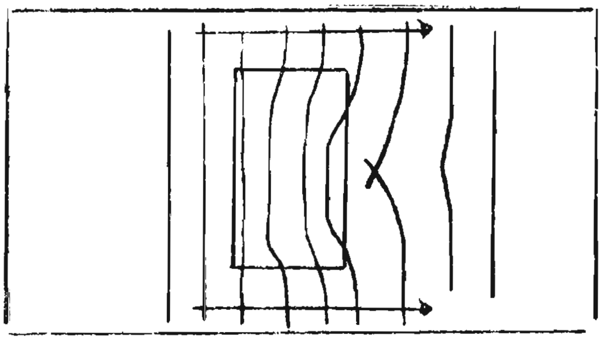


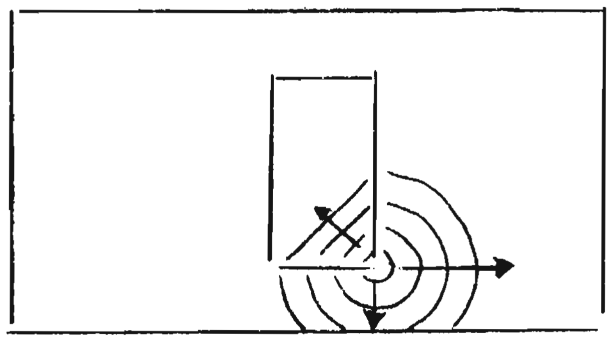
Reflection at Convex Barrier

It is not too illogical to guess that if the reflected waves were reversed along their paths they would emerge in the same form as the original incident waves. This can be readily tested out with the concave surface by using the finger as a source in the position of the focal point (F). Waves generated from any other source position (S) will either converge to a point or spread out (from an imaginary point) on reflection from the concave side of the barrier. In the case of the convex side of the barrier the waves will always spread out (from an imaginary point behind the barrier) on reflection.



(iv) The patterns of wavefronts that emerge make it clear that waves travel more slowly over shallow water than deep water. There is a point, of course, at which increasing the depth of water no longer causes the wave to travel faster, for the wave motion only affects a limited depth of water close to the surface.

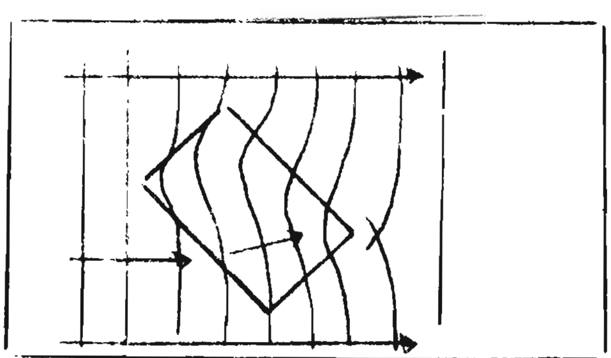


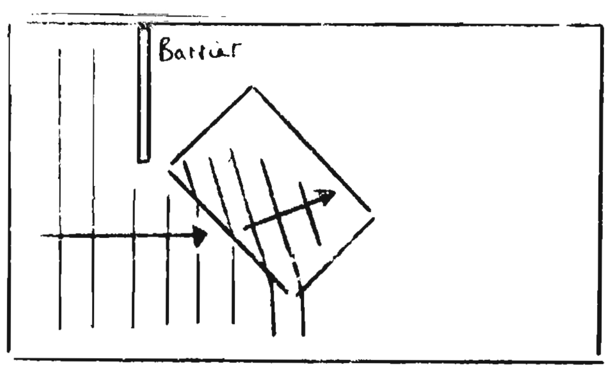


It is interesting for the student to note how the direction of motion of the wavefront tends to bend in towards the shallow region from the sides, but there is no need to confuse the issue by trying to explain it at this state.

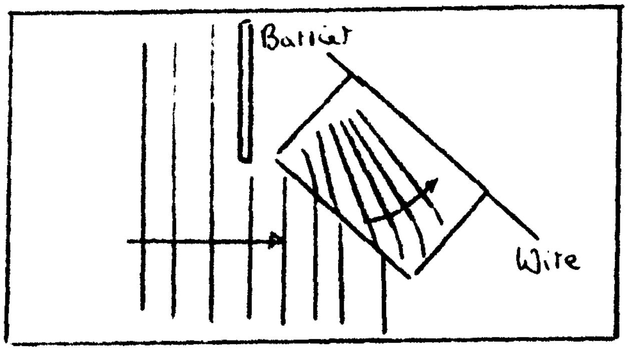
When continuous wavefronts are created one after the other it is possible to see that as the waves are slowed down the wavelength (the distance between the crests) is also reduced. This is even clearer in the next activity where a sloping beach is created.

(v) Because waves travel more slowly through shallow water the direction of motion of the waves is changed if it approaches a shallow region at an angle to its front boundary. This is somewhat more clearly seen if the observations are limited to one boundary of the shallow region by using a suitable barrier. The logic is simply that as the extent of the shallow region that has to be traversed by the wavefront increases, so its retardation behind the normal wavefront passing through deeper water also increases.

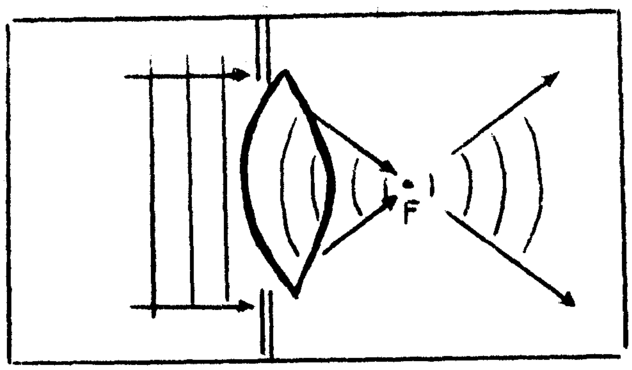




Creating a shallow beach with the glass plate exaggerates the bending effect even more, as the velocity of the wave is reduced and the direction of motion changes more sharply with ever decreasing depth. It also accentuates the reduction in wavelength as the velocity of motion decreases.



(vi) Creating a biconvex region of shallow water causes the incident wavefront to be slowed down considerably at its midpoint resulting in the emerging wavefront being sufficiently bent to converge on a focal point (F) before spreading out again.



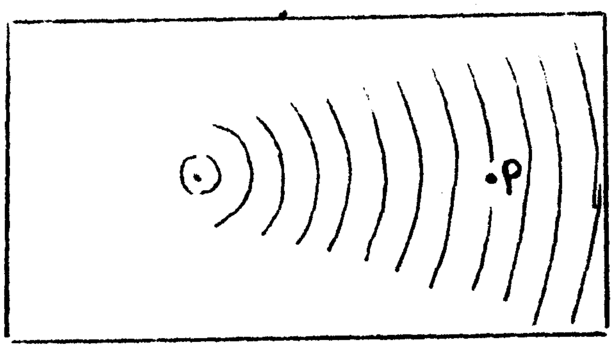
The student may have some initial difficulties in determining the shape of the resultant pattern. Don't ignore these difficulties. The waves do have edge effects, tending to bend into unexpected areas and to continue ultimately as though the obstacles do not exist. These are all realities that are investigated more thoroughly later. Explain to the student that we are trying to indicate the general behavior of the wavefronts, and that many of the details we can sort out once we have determined the general pattern.

3.13 Velocity, Frequency and Wavelength

(i) Students will probably guess quite happily that regardless of the frequency with which wavefronts are created that they will travel at the same speed across the surface of the water.

It is noted that while the rate of vibration of the source remains steady that the wavefronts are separated from one another by the same distance, which is referred to as the wavelength of the motion. With a slow vibrating source the wavefronts are spaced well apart, and it seems a very natural result that a wave of fairly large wavelength should be produced. Equally well a rapidly vibrating source produces a rapid sequence of wavefronts and hence a wave motion of short wavelength.

(ii) Setting two sources vibrating at the same point, but at different rates, creates two waves of different wavelength simultaneously. As the wavefronts move forward side by side it is clear that they move forward with the same velocity, regardless of the frequency of the sources and the wavelengths of the motion. It therefore emerges, somewhat as anticipated, that the velocity of the wave motion is a constant so long as the depth of water is kept constant.



While discussing the relationship between frequency and wavelength it is very relevant to discuss how the frequency of the vibrating source is related to the rate at which wavefronts pass any fixed point (such as P) in the path of the oncoming wave. Consider the motion in the diagram. Regardless of how long the vibrations have been produced the motion will always look the same, and yet every time a vibration occurs a new wavefront appears. It follows that if in one second 20 vibrations are produced that 20 new wavefronts must also have been produced. In order that the pattern should remain the same, 20 wavefronts must have moved past the point P in order to accommodate the 20 newly formed ones. It therefore follows that

the frequency of the vibrating source is also the frequency with which waves pass a given point. When we refer to the frequency of a wave motion we therefore also refer to the frequency of vibration of the source, the frequency of displacement of any point (P) in the path of the wave, and to the frequency with which wavefronts pass any given point (P), all three having the same frequency.

(iii) In a typical experiment the wavelength of the pattern on the floor for the high frequency motion was observed as being 2 cms. The actual wavelength of the water waves is thus given by:

$$\frac{\lambda_1}{x_1} = \frac{y_1}{y_1 + y_2} \qquad \text{where } y_1 = 50 \text{ cms}, \; y_2 = 60 \text{ cms}, \; x_1 = 2 \text{ cms}$$

$$\lambda_1 = \frac{50 \times 2}{110}$$

$$\lambda_1 = 0.9 \text{ cms} \quad \text{\_\_\_\_\_\_} \quad (1)$$

Similarly the wavelength of the pattern on the floor for the low frequency wave was observed as being 5 cms. The actual wavelength of the water waves in this instance is thus given by:

$$\frac{\lambda_2}{x_2} = \frac{y_1}{y_1 + y_2} \qquad \text{where } y_1 = 50 \text{ cms}, \; y_2 = 60 \text{ cms}, \; x_2 = 5 \text{ cms}$$

$$\lambda_2 = \frac{50 \times 5}{110}$$

$$\lambda_2 = 2.3 \text{ cms} \quad \text{\_\_\_\_\_\_} \quad (2)$$

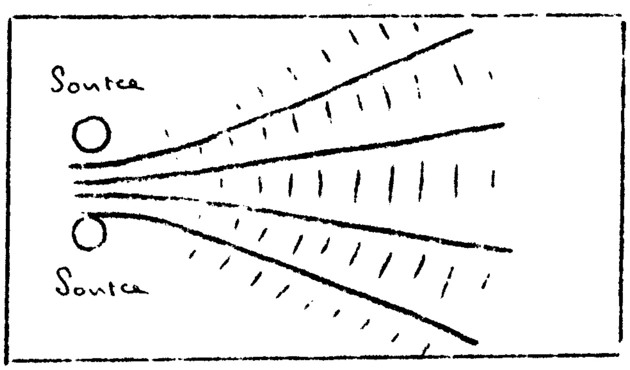
(iv) The two motions are stopped by the same rate of rotation of the stroboscope indicating that both motions have exactly the same frequency. This is an important finding which will have important applications in optics.

3.20 INTERFERENCE AND DIFFRACTION

3.21 Interference and Diffraction

(i) Give the students sufficient time to play a little with the vibrators. Only a few will notice the interference patterns produced, without any guidance, but it is well worthwhile giving such budding scientists the chance to experience the pleasure of discovery. If no one emerges as a discoverer you might take particular note of the pattern produced by one group, and ask the other groups to see if they get similar patterns. Any such device which helps the student to feel that he is really breaking new ground usually produces stimulating results.

Bring the students together to discuss their observations. Hopefully they will have all seen the strong bright lines created between the sources that are typical of interference patterns. Changing the separation of the sources alters the closeness of the interference lines, but does not eliminate them.



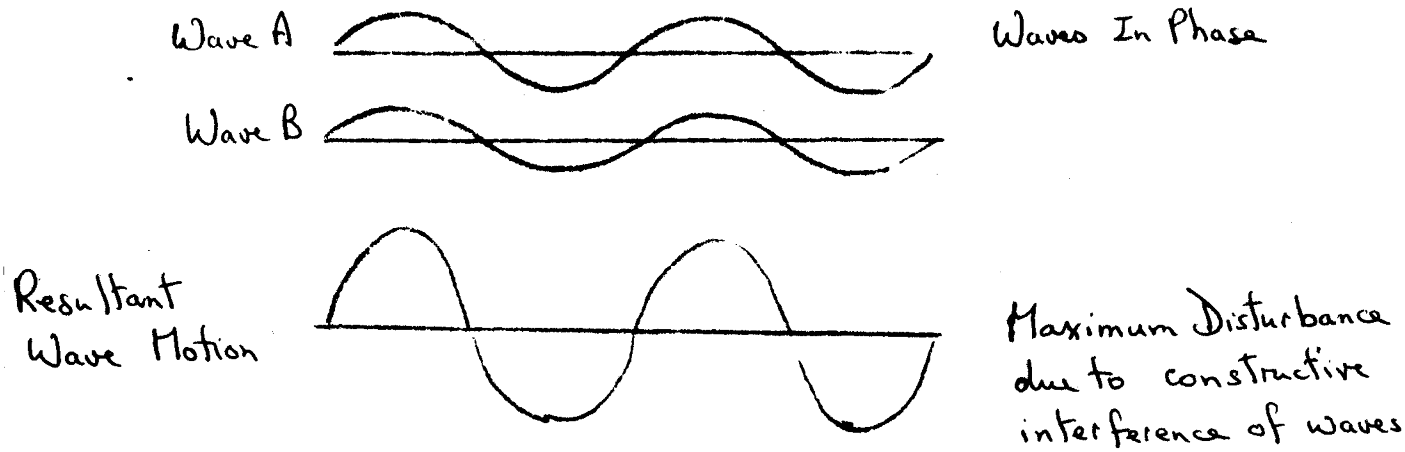
You might start off by asking how two wave motions might affect one another. It may well be that many will be unaware of how waves can affect one another at sea, and this makes a good starting point.

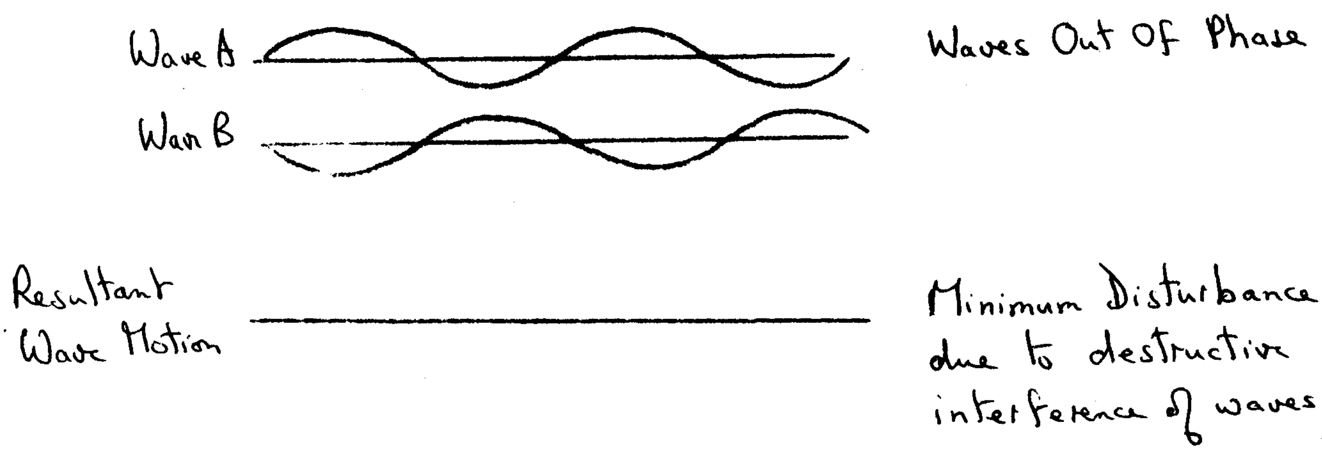
According to scientists the wind can create waves at sea to a maximum height of about 16 meters. Beyond this height the wave usually topples or has its top blown off by the wind. However, much higher waves have been recorded. Thus in 1933 a naval tanker the "Ramapo" caught in a Pacific typhoon was able to make meticulous trigonometric recordings of the height of waves, and a succession of waves was noted varying from 27 to 37 meters from trough to crest. It is quite possible that even higher waves have been seen. The

success in this story is simply that someone not only lived through the storm but was able to make exact recordings for posterity. Some insight into how such waves can arise is found in a more recent report from the ship "Michelangelo" sailing through an Atlantic gale in 1966. The general height of the waves was about 10 meters when suddenly a wave 20 meters high bore down on the ship ripping a hole 10 by 20 meters in the bridge, crumbling steel walls in the ship's interior, and killing three people.

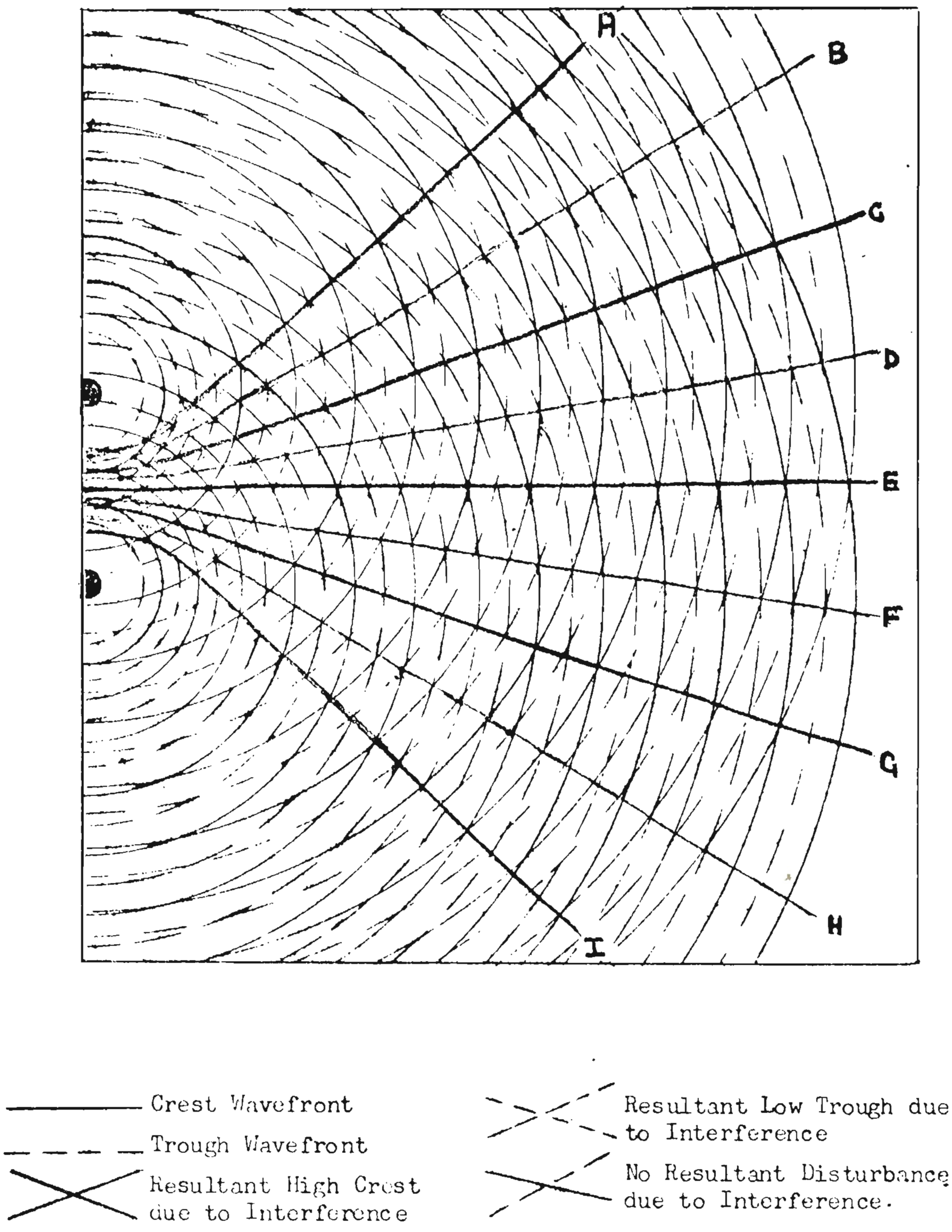
The sea is in fact the meeting point of many wave motions created by storms and other disturbances, and such motions may remain in existence for considerable periods of time. When these motions meet one another they superimpose creating momentary regions of calm and momentary "killer waves", depending on how they combine.

Applying such ideas of wave superimposition to waves in a ripple tank we would expect the vertical displacement of one motion to be affected by that of a second motion. If two identical wave motions are in phase with one another, and superimpose, we would expect the resultant motion to have double the displacement of either. However, if the same two wave motions were exactly out of phase with one another, and superimposed, we would expect the motions to cancel one another out.





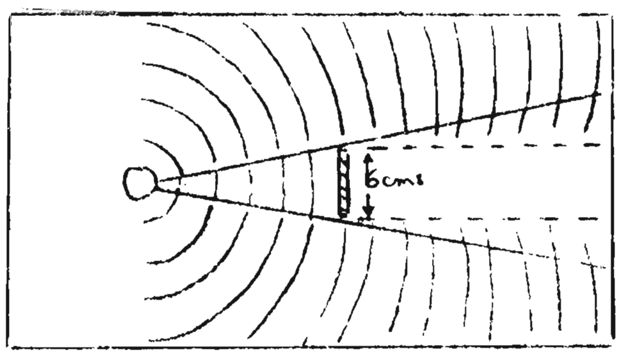
Working on the supposition that waves in the ripple tank behave in this way it is possible to produce drawings of the two wave motions overlapping each other, noting at a given instant just where the crests of one motion overlap those of the other, creating a maximum disturbance of the water, and similarly where the crests of one motion overlap the troughs of the other motion creating a minimum disturbance of the water. Joining together points of maximum disturbance it is seen that these occur along lines A, C, E, G and I, while joining together points of minimum disturbance


A
B
C
D
E
F
G
H
I
Crest Wavefront
Trough Wavefront
Resultant High Crest due to Interference
Resultant Low Trough due to Interference
No Resultant Disturbance due to Interference.

it is seen that these are along lines B, D, F and H. We thus have lines of maximum and minimum disturbance occurring alternately, and it is these which create the effect which the students have seen for themselves.

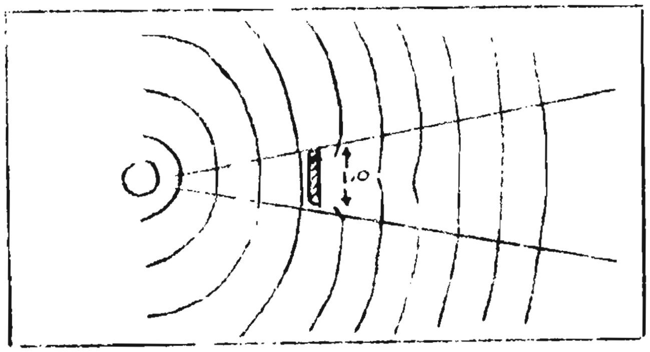
(ii) Careful observations show that when waves strike a barrier that a shadow zone, where wavefronts are almost nonexistent, does exist. With a 6 cm barrier and a low frequency wave it is fairly clear that the edge of this zone does not correspond to the edge of the theoretical shadow that has already been indicated. The wave motion in fact bends into the shadow zone.

High frequency waves do not bend as much as the low frequency ones, and the edge of the actual shadow zone is much closer to the edge of the theoretical shadow. Many students will be able to note the bending of the direction of motion, but will not be able to see a distinct difference between the bending created by the two motions of different frequencies. Don't worry about this as the point will emerge fairly clearly during the succeeding experiments. Above all don't tell the student what he should have seen, but didn't. He can always return to this experiment, as and when his subsequent observations give him greater understanding of what is happening.



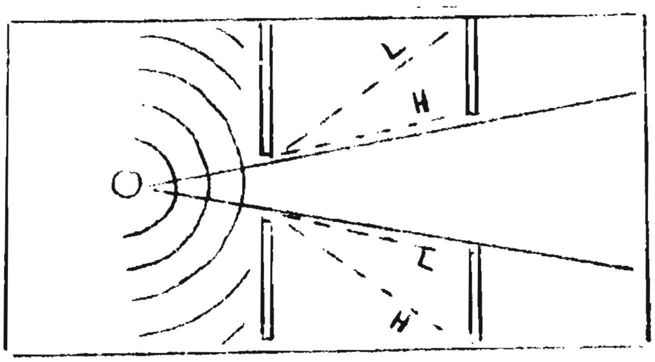
(iii) Repeating the experiment with a barrier 2.5 cms long it is noted that the bending of the waves into the theoretical shadow zone is much more pronounced for both wave motions, and once again is greatest for the low frequency motion.

The bending effect is so great with the shortest barrier (1 cm long) that the wavefronts join together after the barrier, almost as though the barrier had not existed.



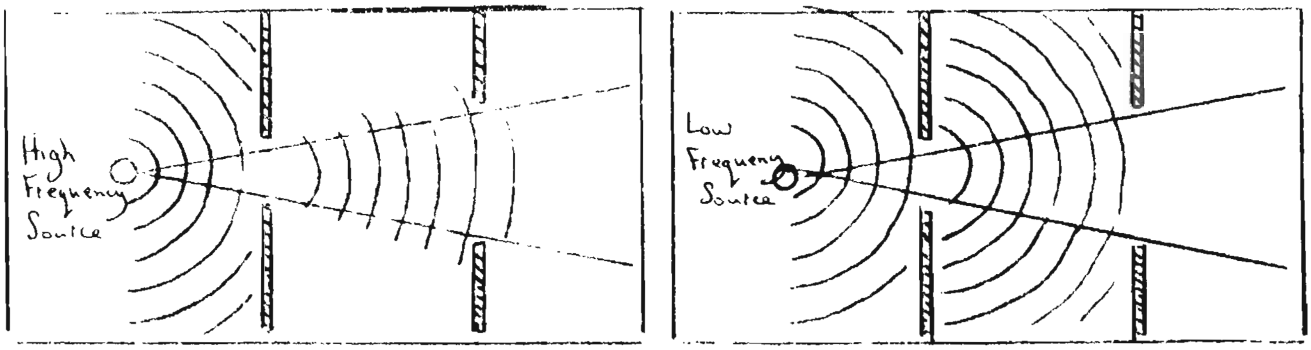
The conclusion drawn is that waves do bend around obstacles, the bending increasing in magnitude as the frequency of the wave motion is reduced and as the object gets smaller and smaller. Alternatively, the bending effect is far less obvious when the wave motion has a high frequency, and the obstacle is large. We might tell the students that we generally refer to this type of bending of waves as diffraction.

(iv) Observing the bending of the wavefronts with a large aperture (7 cms) is the same as observing the bending with two barriers, and the effect is highly predictable. In actual fact students may find it easier to observe the difference in the amount of bending between the high and low frequency wave motions with apertures, particularly as they are made smaller and smaller. With high frequency waves the shadow zone is almost the same as the theoretical one marked out, while with the lower frequency waves the bending is somewhat greater.

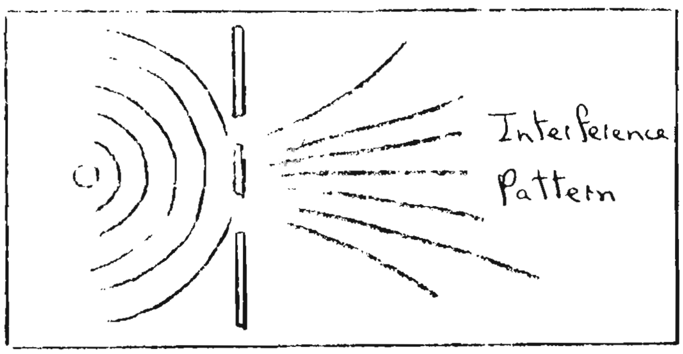


L Limit of bending into theoretical shadow zone with low frequency waves

H Limit of bending into theoretical shadow zone with high frequency waves



It is because of this property of small apertures acting as sources of new waves that two apertures placed close enough together will act as two sources of wave motion which can produce a typical interference pattern.



4. OPTICS

One of the major aims in the presentation of this topic is to give students a real feeling of the way in which science develops. Two theories, the Corpuscular Theory and the Wave Theory, are presented from the beginning. Students will probably find that each theory appears to explain initial phenomena such as reflection and refraction equally well. Don't encourage students to decide at an early stage that one theory is better than the other, as it would almost certainly be founded on unscientific guesswork. On studying the phenomenon of interference the first real doubts about the Corpuscular Theory will be created at the same time as the evidence for the Wave Theory will be reinforced.

The final death blow to the Corpuscular Theory will be given when students learn the relative values of the velocity of light in air, water, glass and other such media. At this point it will be important to qualify the findings. Students must not feel superior to Newton, because they discovered something which he missed. Newton was probably one of the greatest scientists of all time, pushing forward the boundaries of science in all directions.

The point to be realized is that scientific theories are used to explain physical phenomena. They may do this extremely well, but it is natural that theories give rise to more detailed experiments intended to test the theories fully. When a theory fails there is often great excitement, for this is generally the first sign of a breakthrough resulting in new knowledge and new theories. Students must fully understand the difference between the facts of experimental observation and the theories that explain them. Theories must always be considered as developing, even if they hold for a hundred years or more. Even experimental observations should be qualified, and the student should realize that as observations become more accurate, experimental conclusions may become more sophisticated.

The Wave Theory is an excellent example of the need for scientists to be open minded. Towards the end of the 19th century the Wave Theory gained considerable momentum as it predicted and explained more and more phenomena. In 1873 Clerk Maxwell presented a series of very convincing arguments

(mathematical equations) indicating that light was not only a wave motion, but an electrical wave motion. This was confirmed in 1888 by the German physicist Hertz in a series of experiments which ultimately led to an electrical Wave Theory explaining not only light phenomena, but all types of electromagnetic disturbances such as radio waves and various types of transmissions such as gamma rays, x-rays, ultraviolet, visible and infra red rays.

The Wave Theory was probably one of the greatest advances in scientific theory at that time. In fact it was so successful that there was a tendency to look upon it as fact, rather than theory. However, around 1900 there was a series of discoveries related to the way in which light is absorbed and emitted by materials. These could not be explained by the Wave Theory, and led in 1905 to further new theories by the great Einstein, who suggested that light is emitted from bodies as a shower of particles (photons) produced in definite energy packets (quanta).

At first glance this new Quantum Theory might seem like a reversion to the old Corpuscular Theory. It is true that it is a form of Corpuscular Theory, but much more sophisticated than the old Newtonian Theory. In actual practice scientists nowadays tend to use the Wave Theory and Quantum Theory according to the problem being investigated. How long will such a Dual Theory describing light behavior be able to exist? Until new discoveries are made to clarify the way ahead.

These comments are made, to explain the need for students to make observations with reasonable open mindedness, in much the same way as scientists in the past. It is worth recalling that many major scientific breakthroughs have been met with considerable resistance by conservative minded people, including many scientists. It is also true that scientific and technological advancement has often been retarded by the failure of the relevant authorities to appreciate, or analyze, new discoveries.

It is therefore hoped that Optics will be presented to the student with these ideas very much in mind. Let the student see the uncertainties of Optics at the same time that he discovers the apparent certainties. Let him see the strength of the Wave Theory for himself. Then, and only then, you might discuss some of the points mentioned above, not as facts to be remembered, but simply as information showing how scientific theories continue to evolve.

4.10 PROPAGATION, REFLECTION, REFRACTION

4.11 Propagation

(i) You might actually introduce the topic by discussing how light is created. Do all objects emit light? A discussion of what can be seen in a completely darkened room before, and after, an electric light bulb is switched on will give some ideas. The electric light bulb is clearly the source of light emissions, but other objects are seen due to the fact that light falls on them (being reflected from the object to the eye).

Light may originate from many sources, such as electrical filaments, electrical discharge tubes (neon lights), flames and other hot bodies. In each case some form of energy conversion takes place to produce light, which might therefore be considered as a form of energy.

Light is emitted in all directions from a given source. If the student has any doubt about this get him to hold a piece of white paper in the vicinity of the holes in the lamp housing, and ask him to explain what causes bright patches of light on the paper. If he wonders at this stage why he can't see the light rays travelling through the air, but why he can see them clearly when they strike a paper surface, congratulate him on his power of observation, and suggest that this is well worth investigating. This problem, and several others, have been delayed until the end of the treatment of Optics to insure that the initial approach is able to concentrate mainly on the problem of which of the two theories of light is considered preferable.

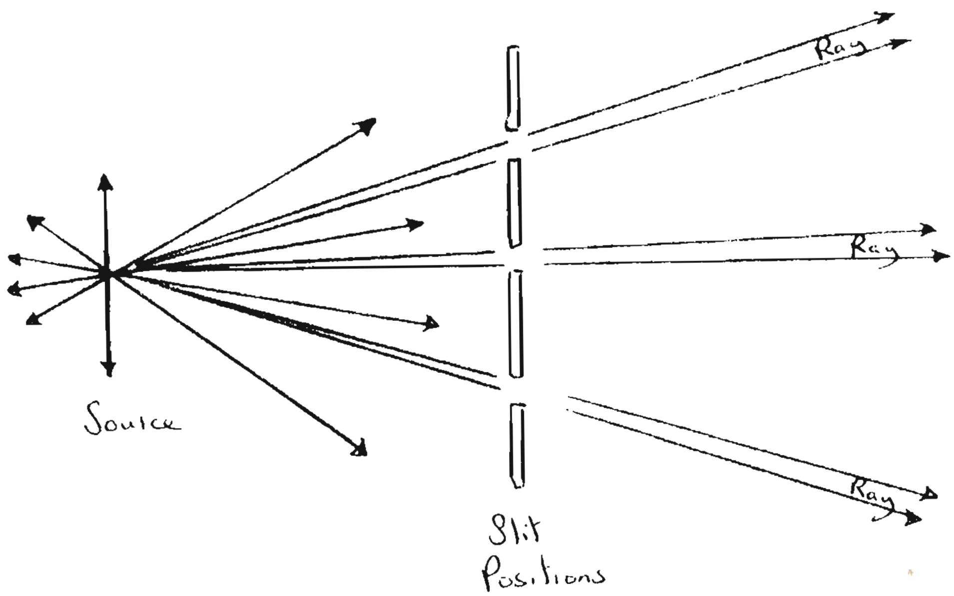
If lines are drawn from the source of light (the filament) towards, and beyond the barrier, it is possible to indicate a theoretical shadow zone. The actual shadow created by the barrier corresponds with the theoretical shadow indicated. In other words, at this stage light does not appear to bend into the theoretical shadow zone.

However rapidly the barrier is removed from the light path it is noted that light immediately fills the original shadow zone. Light must clearly travel very rapidly. You might show your students how to compare the velocity of light with that of sound. Get one student to take a hammer to a drum, located some 300 meters away from you and your group of students. If he strikes the drum it will be noted that the sound arrives at the group after the motion of striking is observed. It follows that the velocity of light

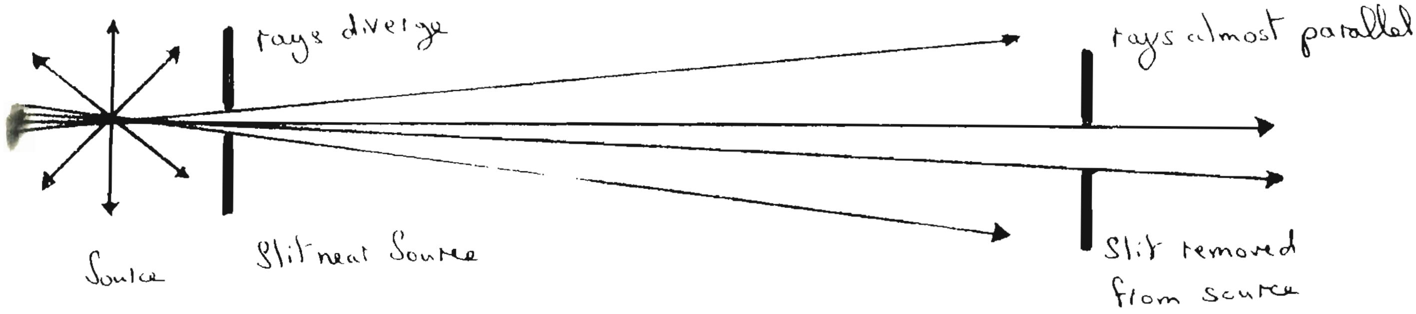
is greater than that of sound. In actual fact the velocity of sound is approximately 340 meters/second, while that of light is 300,000,000 meters/second.

It is interesting at this point to discuss how thunder is always preceded by a flash of lightning. If it is assumed that a flash of lightning reaches us almost instantaneously, followed 3 seconds later by the sound of thunder, we calculate that the source of thunder and lightning is about 1,020 meters away (3 x 340 meters). If the time lapse between lightning and thunder is only one second, the source of the disturbance is 340 meters distance away. With no time lapse between the two you can stop worrying. You will have been struck.

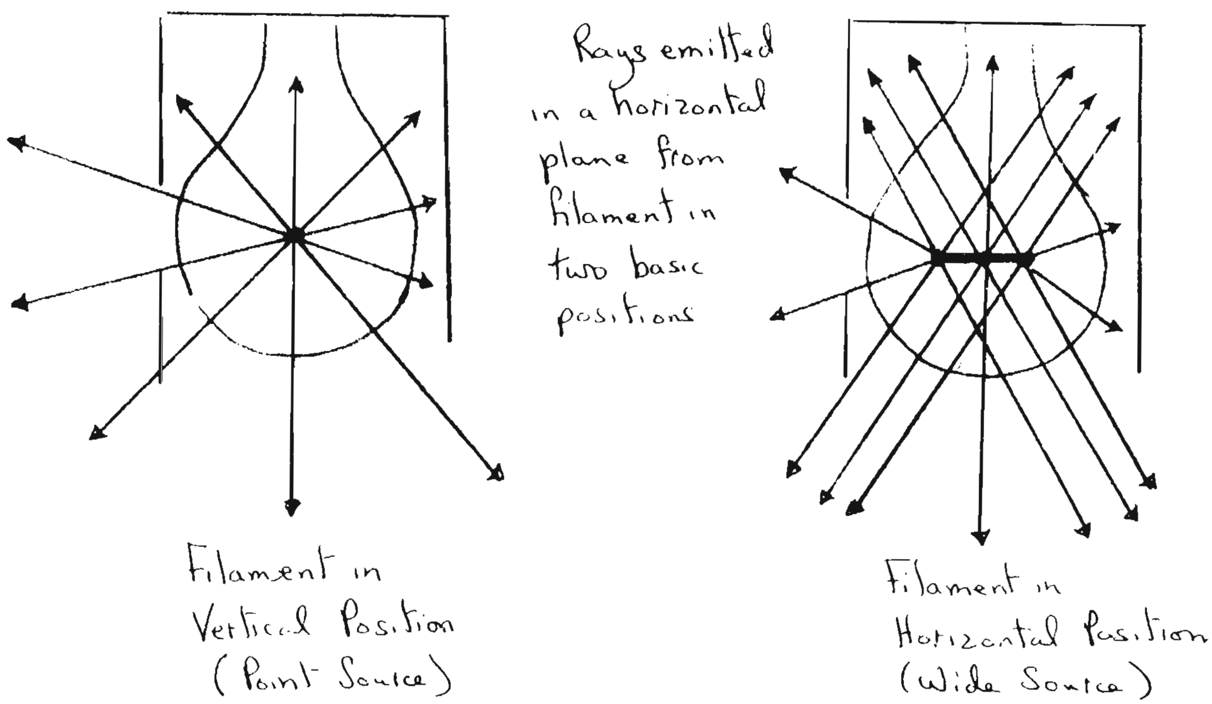
(ii) Placing the slit in various positions it is noted that the rays can always be traced backwards to the light source. Light clearly travels in straight lines.



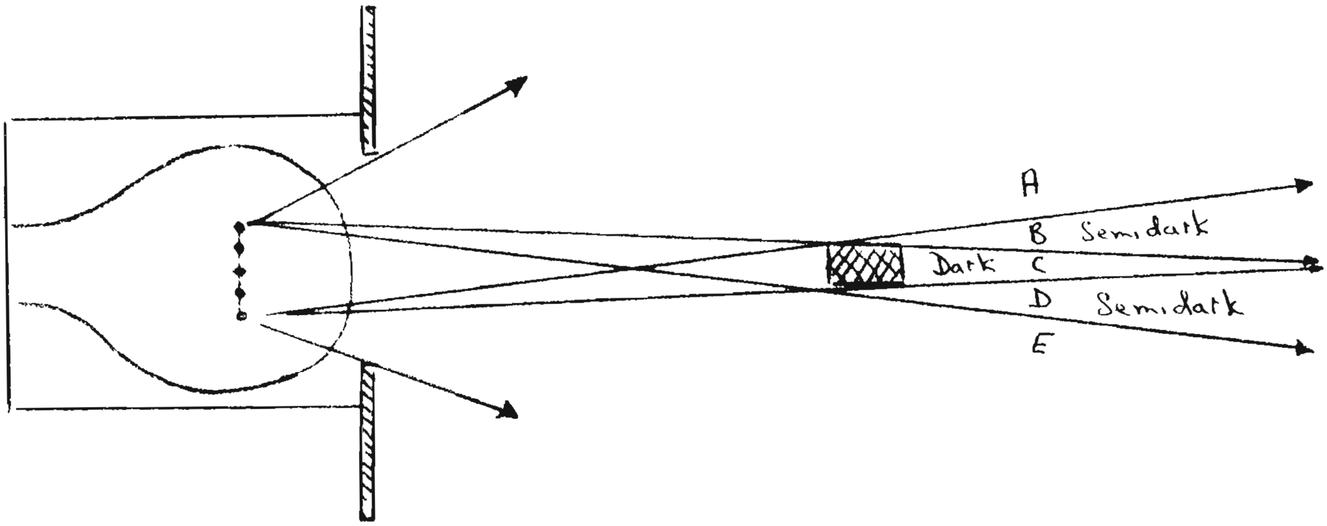
It is noted that the shape of the ray from a slit depends upon the closeness of the slit to the source. Light passing through a slit placed close to a source will diverge whereas that passing through a slit some distance from the source will appear almost as parallel rays.



(iii) When the lamp filament is in a vertical plane it effectively acts as a point source for rays spreading out over the horizontal plane of the table. However, when the filament is in a horizontal plane it acts as a wide source, with all points on the filament emitting rays in all directions.



With the point source sharp edges are observed at the edges of the shadow, while the shadow itself is uniformly dark. With the wide source, however, the edges of the shadow are not as clearly defined, and more careful observation shows that the shadow is not uniformly dark, but consists of two semidark regions and one dark region. Lines can be drawn to mark out the edges of the shadow, and you might suggest your students do this. They will find that if these are extended backwards they will join together at the extreme ends of the filament.



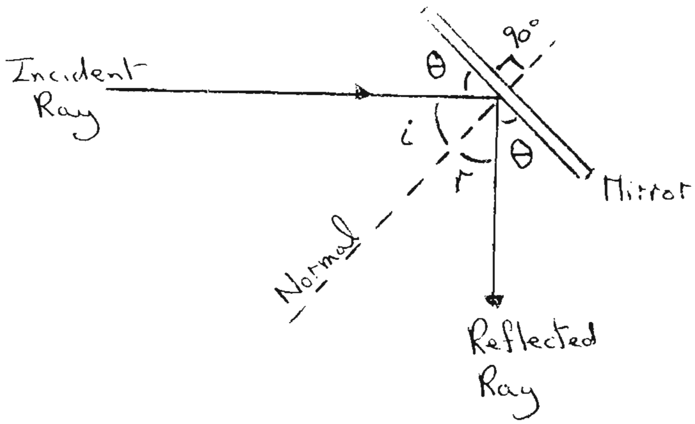
The theoretical explanation is fairly simple if the line filament is considered as a series of point sources (1 to 5) joined together. By considering each point source in turn it will be seen that light from none of the points can enter the region C, and this is therefore the darkest area. Light from some of the point sources, but not all, can enter regions B and D, and these are therefore only semi dark, while regions A and E are bright, since light can reach these from all the point sources.

It is important that students should recognize such edge effects, avoiding any subsequent confusion of these effects with those of diffraction.

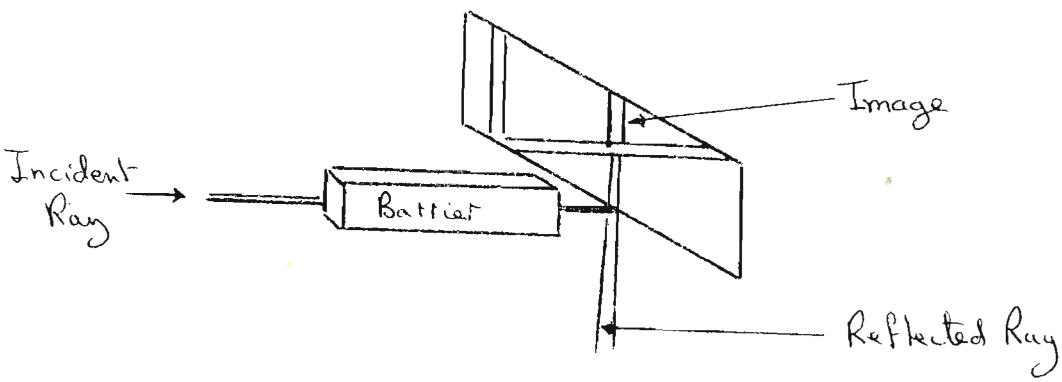
(iv) The major observation is that light travels in straight lines. It light was composed of small particles travelling at high speed this is what we would expect. On the other hand if light travelled as a wave motion we would expect it to show a very definite tendency to bend around obstacles, rather as we have seen in the ripple tank. However, if the frequency of the motion was very high the bending would be limited, and shadow boundaries would be very close to the edges of the theoretical shadow zone. The wave theory therefore starts out somewhat hesitantly, for there is no apparent bending of light rays around an obstacle , and this can only be explained by the Wave Theory if the frequency of light is very high.

4.12 Reflection

(i) If the student makes sufficient observations he will soon guess that the reflected ray always comes off the mirror at the same angle (θ) to the surface as that at which the incident ray strikes it. There is no need at this stage to confuse the issue by drawing normals to the surface and talking about angles of incidence (i) and reflection (r), as this seems somewhat artificial, and irrelevant to the problems being studied. They should only be brought into use as and when the need is clearly seen by the student.

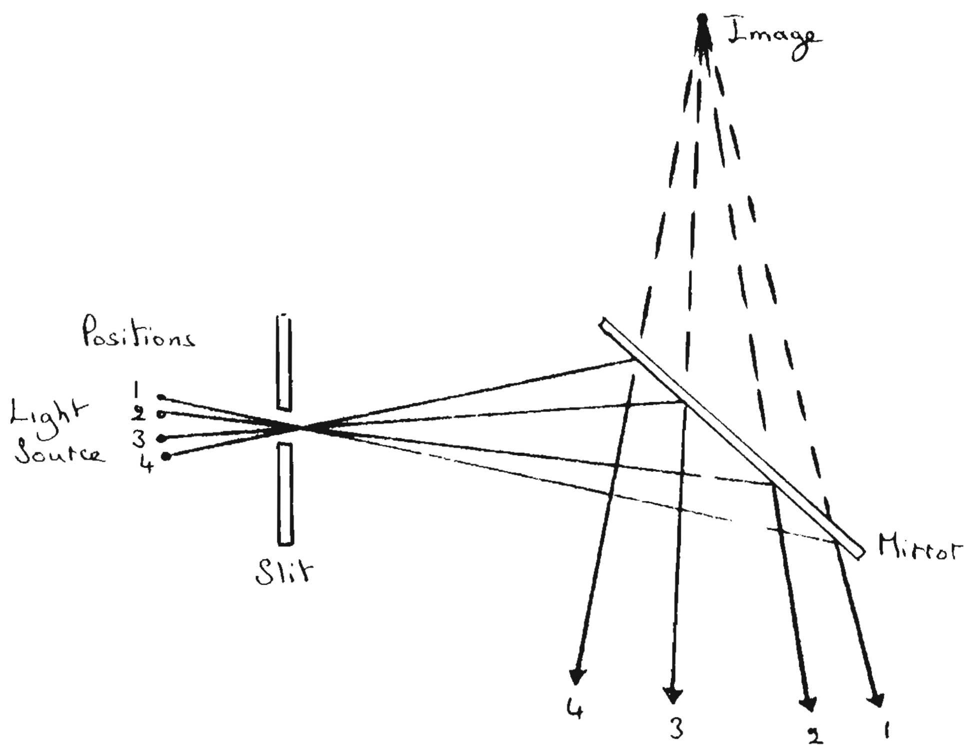


(ii) Regardless of the inclination of the incident ray to the mirror, it always appears that the reflected ray emerges from an image of the slit somewhere behind (some might say inside) the mirror. This establishes that images and reflected rays are connected, hence the rather loose term reflection which may refer to the ray or image.



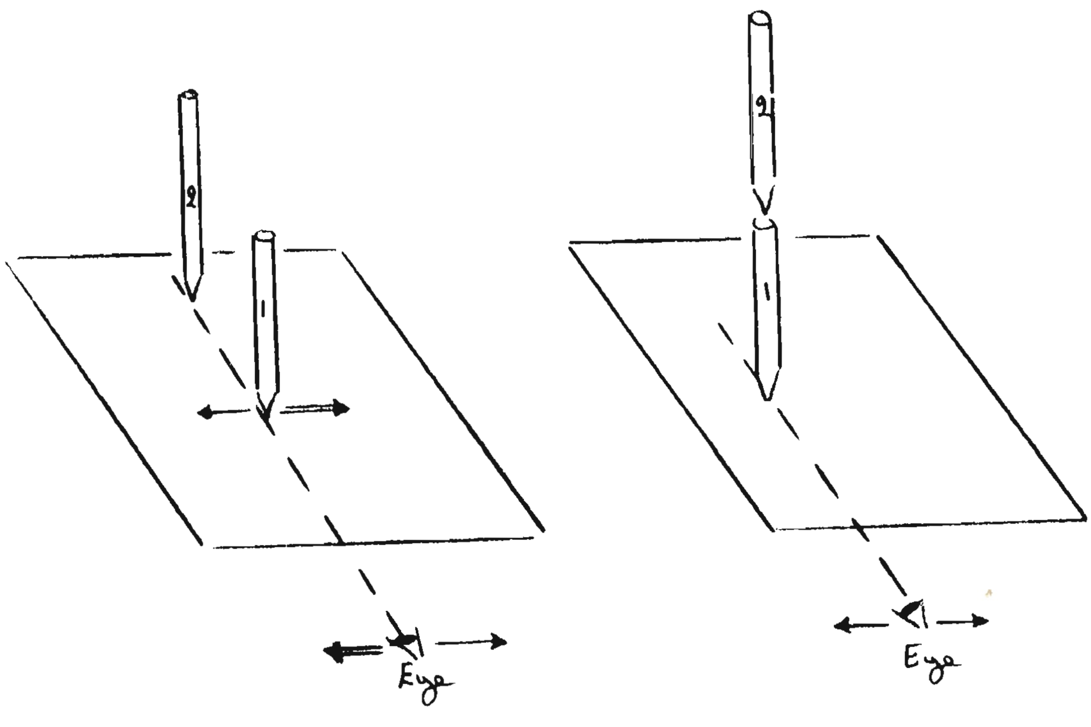
When the electric lamp is switched off the bright reflected ray disappears. The image of the slit, however, remains, although the center portion is no longer as brightly illuminated.

(iii) The theory proposed tends to be confirmed when the electric light source is placed in two different positions in order to trace two daylight rays to the mirror, and from there to the eye. All such reflected rays appear to come from the same point behind the mirror, and in fact appear to come from the image. This is confirmed by moving the electric lamp from one position to another while still viewing the image of the slit. The image position is unaffected.

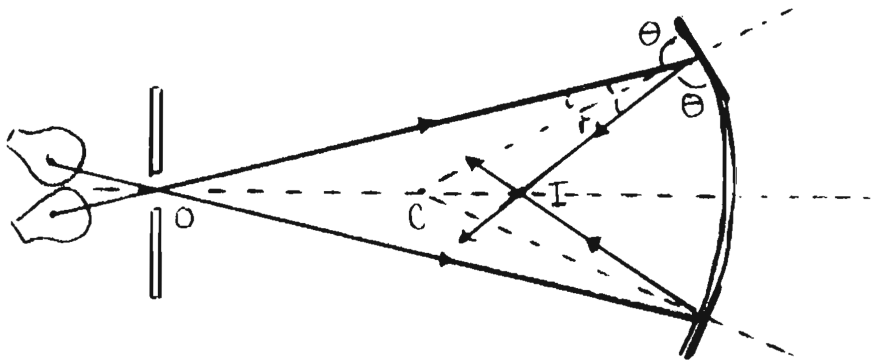


The position of an image may be found, without using actual light rays from an electric lamp, simply by drawing the direction in which rays are emitted from an object. Remembering how rays are actually reflected at a surface, it is possible to construct the direction of the reflected rays. Extending these rays backwards behind the mirror indicates the position in which one would expect to find an image. It follows that two rays would be sufficient to establish the location of the image.

(iv) It is suggested that the object pin used should be one with a white painted sleeve surrounding it, as the image of this is much more visible in the mirror than that of the steel pin itself. When an ordinary pin (i.e., image pin) is placed behind the mirror in the same position as the image, it is found that the image pin and the image appear to remain joined together as the head (eye) is moved from side to side. With the image pin in any other position the image and image pin separate as the head (eye) is moved sideways. This technique of parallax is extremely useful in locating image positions. The principle may be readily confirmed by taking the two pins with white covered sleeves, and sticking them vertically one in front of the other in the optical board. It is always possible to place the eye in one position where the front pin covers up the rear pin, but moving the head sideways causes the pins to separate. Only when the two pins are in the same position is it possible to move the head sideways without separating the pins.



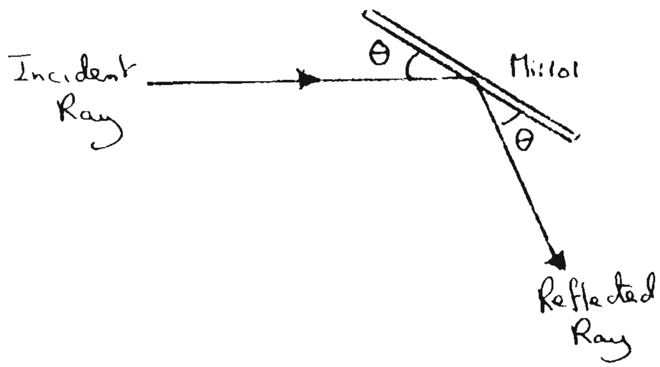
(v) A study of light rays falling on a curved surface will show that the rules of reflection which applied to plane mirror surfaces also apply to curved mirror surfaces so long as we consider only the surface where the light ray strikes it. In this case the image is not located at an imaginary position where the reflected rays intersect, but at the actual intersection of the rays. For this reason we say we have a real image produced by the mirror, whereas in the case of the plane mirror we had an imaginary (or virtual) image.



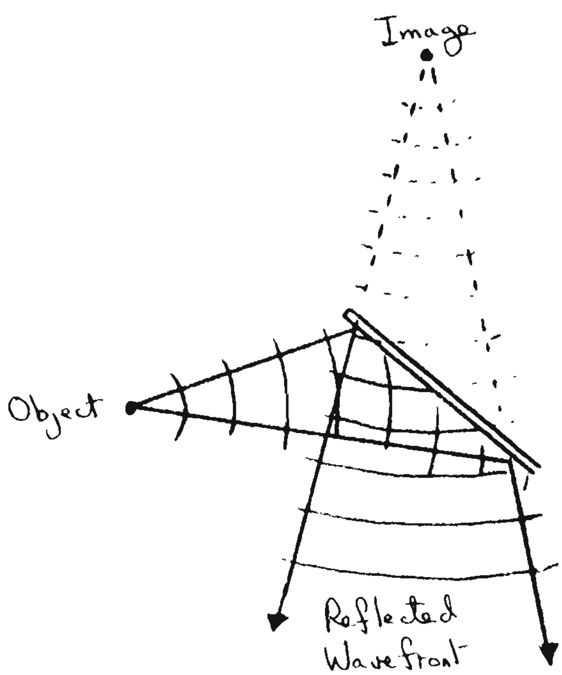
Replacing the slit by an object pin we see an image of the pin in the mirror. It is not illogical to expect this to be located in the position where the rays were noted to intersect, for it is from there that rays originate before reaching the eye. This is readily tested by placing an image pin (without a sleeve) at the point of intersection. Moving the head from side to side it is seen that the image pin and the image appear, by parallax, to be in the same position, thus confirming the position of the image. If the image pin is placed nearer to, or farther away from, the mirror, parallax with the image is lost.

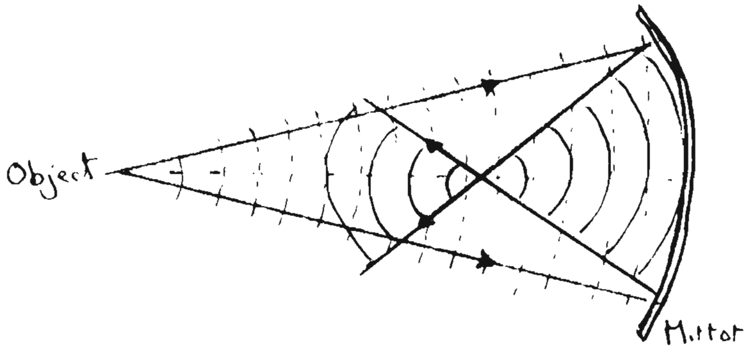
The parallax technique is a very useful method of locating the positions of mirror images. An object is placed in front of a mirror and the image produced in the mirror noted. An image pin is then placed in different positions in front of, or behind, the mirror until one position is found by parallax where the image and image pin move together. The image pin is then located at the same position as the image.

(vi) The way in which rays are reflected may be explained equally well by a Corpuscular Theory or a Wave Theory. Corpuscles, like elastic balls, would be expected bounce off elastic surfaces so that the angle between the reflected ray would be the same as the angle between the incident ray and the surface.



In previous experiments with the ripple tank we have observed almost identical behavior as waves have been reflected at plane and curved surfaces, the direction of motion of the wavefronts corresponding to the direction of the light rays. At this stage there is therefore no reason to believe that one theory might be better than the other.



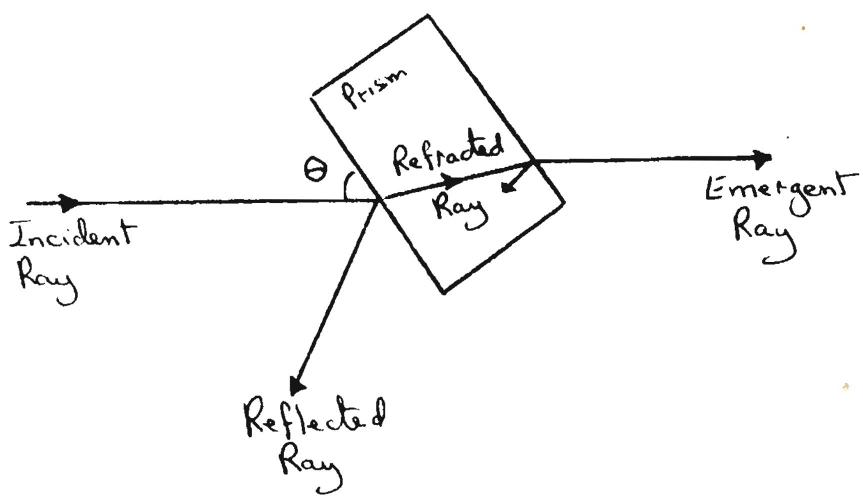

Object
Mirror

4.13 Refraction

(i) Rays are reflected at the front surface of the prism in the same way as from a mirror. The reflected rays appear to come from an image behind the surface of the prism, and this image is bright if the intensity of the reflected ray is bright. This in fact occurs when the angle (θ) between the incident ray and prism is small.

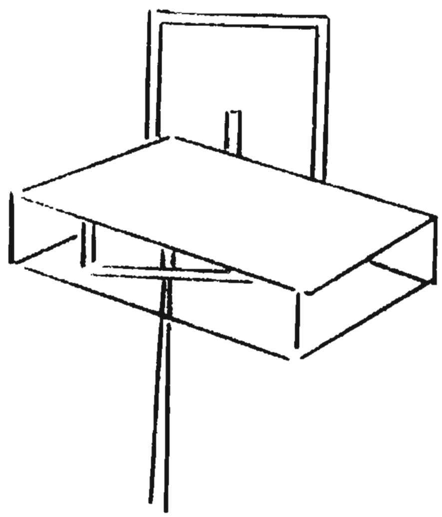
(ii) In order to investigate how rays are transmitted through the prism it is important to place the rough surface of the prism in contact with the paper laid on the surface of the table. If students wonder why, suggest that they lay the prism on its side (with smooth surfaces top and bottom) and see if they can see the path of the ray. If they are inquisitive about this you can suggest that they might like to investigate this later. Details for such an inquiry are included at the end of this topic.

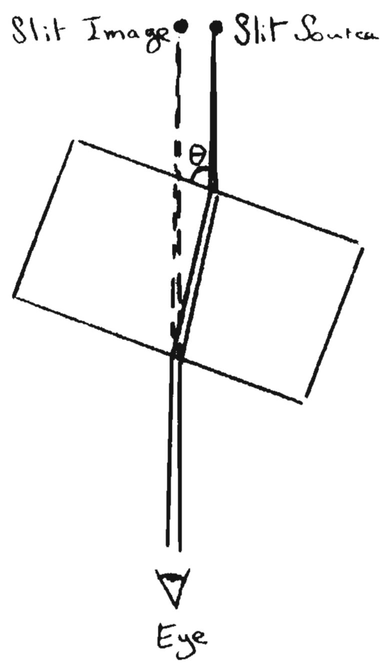
It is not too surprising to find that when the intensity of light reflected at the front surface of the prism is high the intensity of transmitted light is low. Equally well, when very little light is reflected at the front surface (as in the case when the incident ray approaches the surface at 80 to 90°) the intensity of the transmitted light is high.



It will be noted that the incident ray changes its direction on entering the prism and again on leaving it. We say that it is refracted at both surfaces. It finally emerges into the air parallel to the original incident ray. In theory we might expect a reflected ray within the prism, but this is not visible due to the fact that when the angle θ is small, and favors internal reflection, the intensity of the transmitted ray is too low to make any internally reflected ray visible.

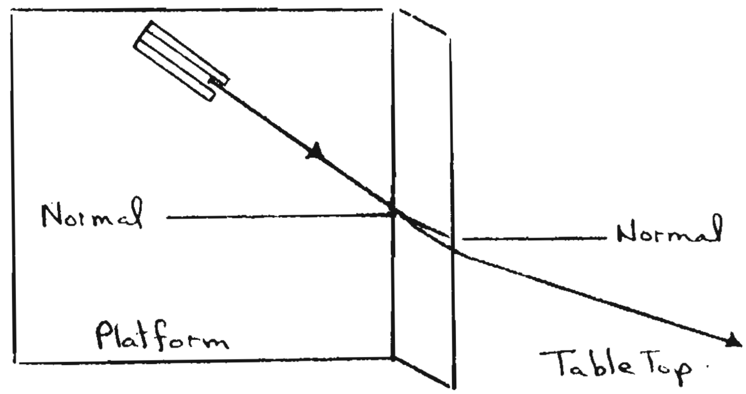
When the incident ray strikes a surface at 90° there is no visible refraction at the boundary. We refer to such a ray, crossing a surface without refraction, as the normal to the surface.





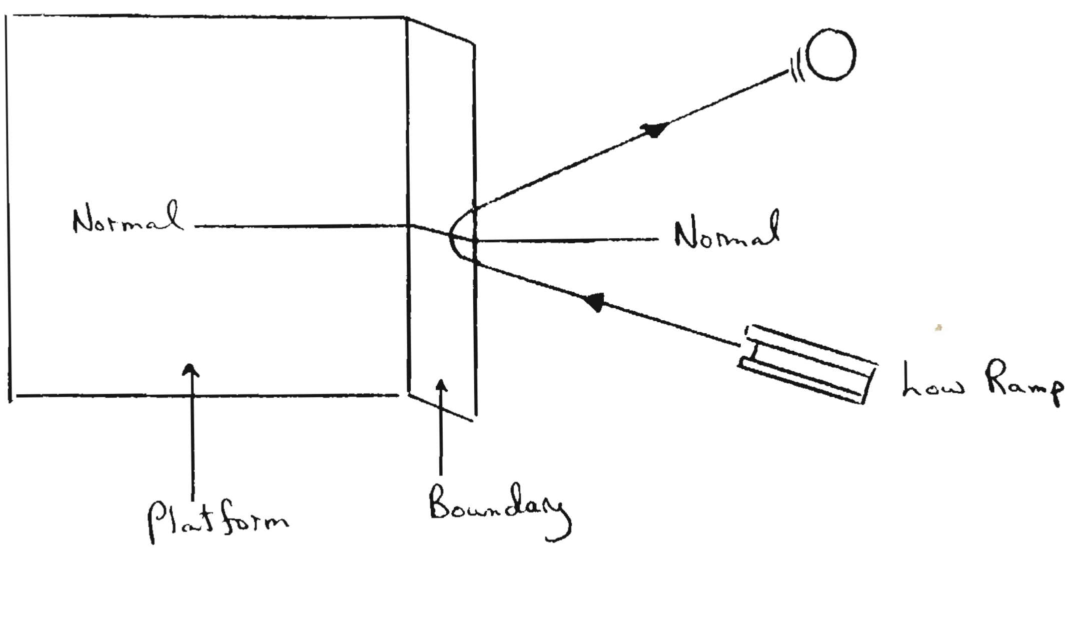
Looking into the surface from which the ray emerges you see a clear image of the slit, and it appears that the ray of light emerges from this slit image without any refraction as it crosses the rear surface of the prism. This is a most fascinating illusion, for on viewing the ray through the top surface of the prism the refraction at the rear surface can be seen quite clearly. The location of the image is once again related to the direction of the rays which actually reach the eye, in this case the emergent rays. This results in the image being displaced to one side of the actual source (slit), and the displacement increases as the angle (θ) between the incident ray and the prism surface decreases.

(iii)

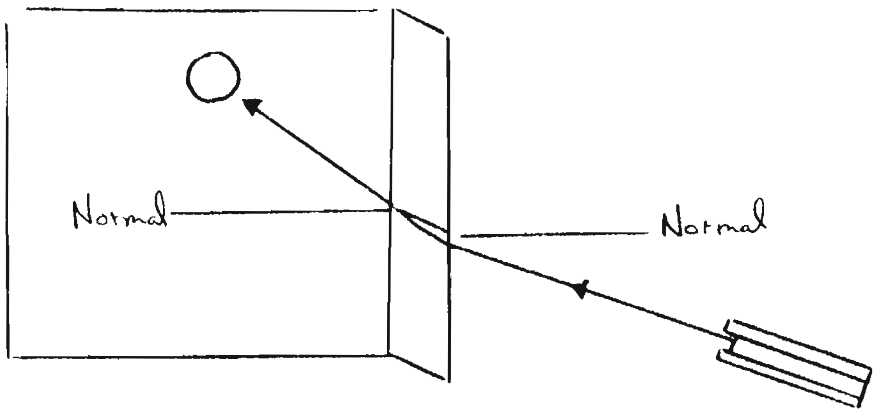


As the ball rolls across the boundary its velocity increases, while at the same time its motion is refracted towards the normal. In other words the model would support Newton's Theory.

The same apparatus may be used to demonstrate the reflection of light according to Newton's Corpuscular Theory. Simply set the platform at a height of approximately 2 cms above the table, and launch the ball bearing from the top of the small ramp towards the boundary slope. The velocity of the ball will be insufficient for it to completely climb the slope, and the ball will therefore be reflected.



Keeping the platform at the same height if the ball bearing is launched once more towards it from the table top, but this time from the top of the large ramp, it will have sufficient energy to climb the boundary and cross the platform, refraction occurring once more at the boundary as the velocity of the ball decreases.

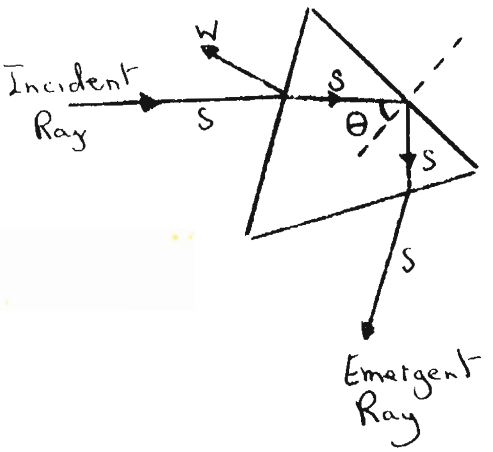


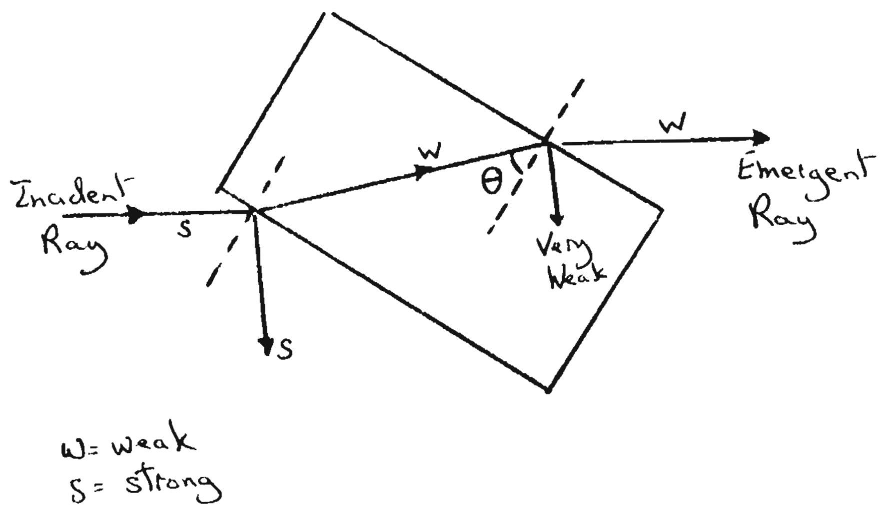
Both Newton's and Huyghen's Theories explain refraction satisfactorily. However, they disagree on one major issue. The Corpuscular Theory indicates that refraction towards the normal in a dense medium is accompanied by an increase in particle velocity. The Wave Theory indicates that precisely the same phenomenon is accompanied by a decrease in velocity. Effectively this contradiction was a major break for it led to a clear choice between the two theories. Unfortunately the velocity of light was not measured until 1850, and the choice between the theories was left in suspension.

We now know that the velocity of light decreases as it passes from air into denser media, and this alone would have destroyed Newton's Theory had the facts been known around 1680. As it was scientists had to wait for a clear answer to the dispute between the two theories, and we might well keep students in equal suspension for just a little longer.

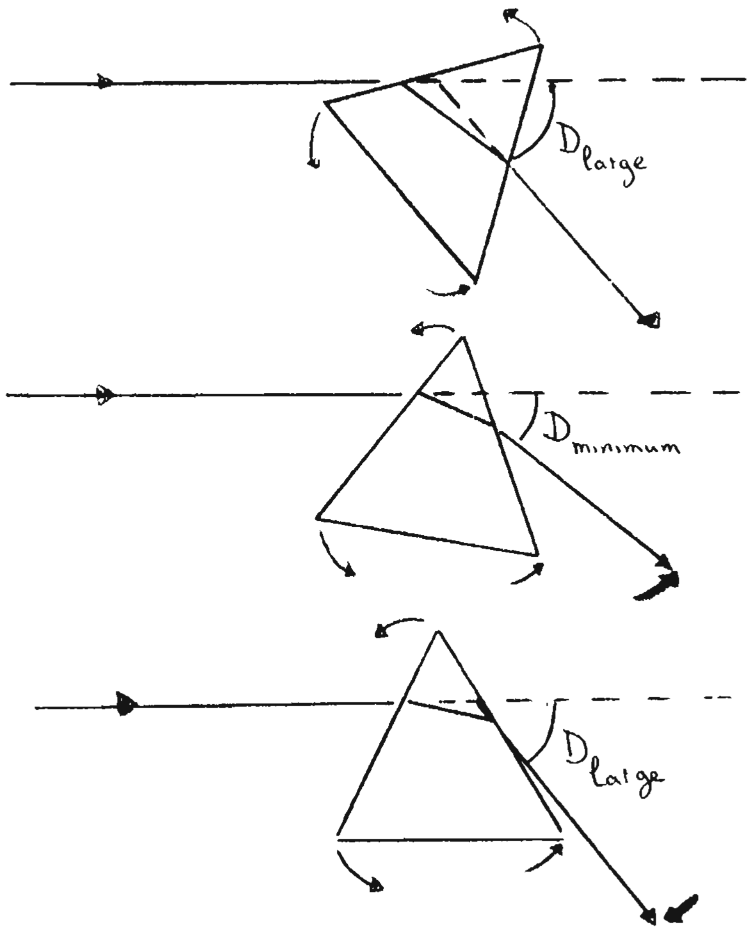
4.14 Color

(i) With the triangular prism it is possible to see quite distinct internal reflection of light rays as they strike the air boundary after travelling through the plastic prism. This is because it is possible for a bright ray of light to approach the boundary at a fairly large angle (θ) to the normal, whereas any light ray approaching a similar boundary in a rectangular prism at an equally large angle (θ) would be relatively weak, due to loss of intensity caused by reflection at the front surface of the prism.

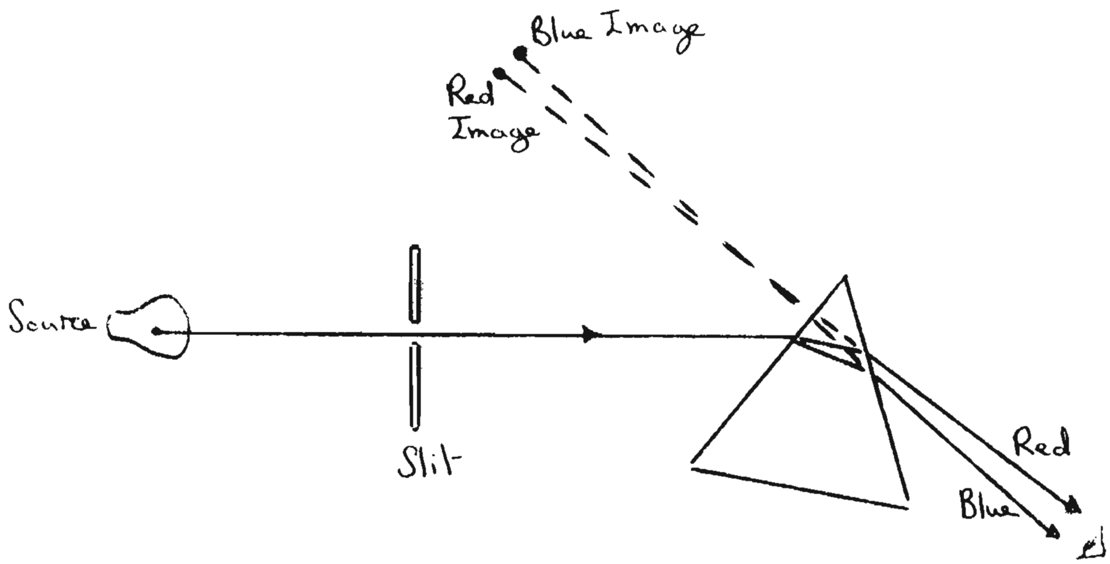




In setting up the prism so that light is refracted at two surfaces, some internal reflection is bound to occur, but total internal reflection, as illustrated above, need not occur. The diagrams that follow indicate the form of behavior of the transmitted light as the prism is rotated in an anticlockwise direction. It will be seen that the deviation (D) of the ray decreases and then increases as the angle between the incident ray and surface of the prism steadily increases. It follows that there is a position of the prism for which the deviation of the light ray is a minimum.



Very close to the position of minimum deviation the breakdown of the emergent ray into individual colors becomes quite distinct. Because of the width of the slit the center of the emergent ray will probably still appear white, but the two edges of the ray will be blue and red respectively, with the blue light being more strongly refracted than the red.



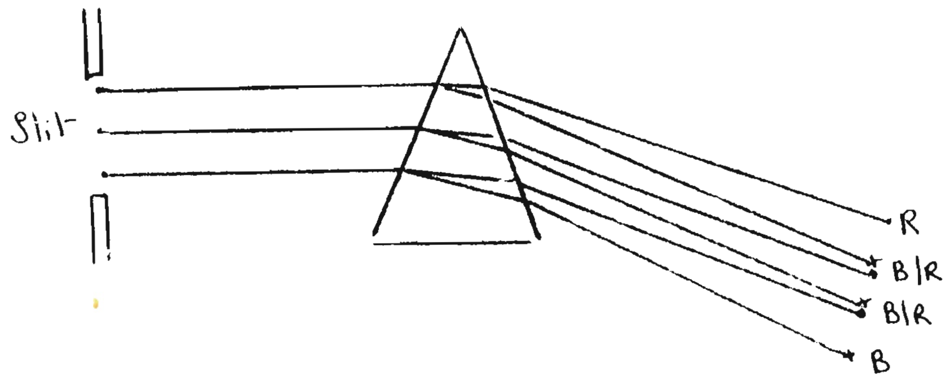
Looking at the image students might be surprised at first to note that the right hand side of the image is blue whereas the right hand edge of the emergent ray is red. Suggest that they determine the position of the image of the slit using a white sleeved image pin and the parallax method. If they then extend the emergent rays back towards the images they will see the relationship of the red and blue images to one another and to the emergent rays.

(ii) Using two prisms to increase the deviation of the rays causes the emergent ray to spread out wider, with the breakdown into colors more distinct. Placing the prisms close together, back to back, so that the deviation produced by the second opposes that produced by the first, eliminates the color from the emergent ray. It seems that the individual colors are brought sufficiently close together by the second prism to overlap one another and reproduce white light. However, if the separation between the two prisms is more than about 1 cm the colored rays are too far apart to overlap, and the emergent ray will still be seen to be colored.

The major point for students to grasp here is that not only can white light be broken down into colored components, but also that those components can join back together (overlap one another) to produce white light once more.

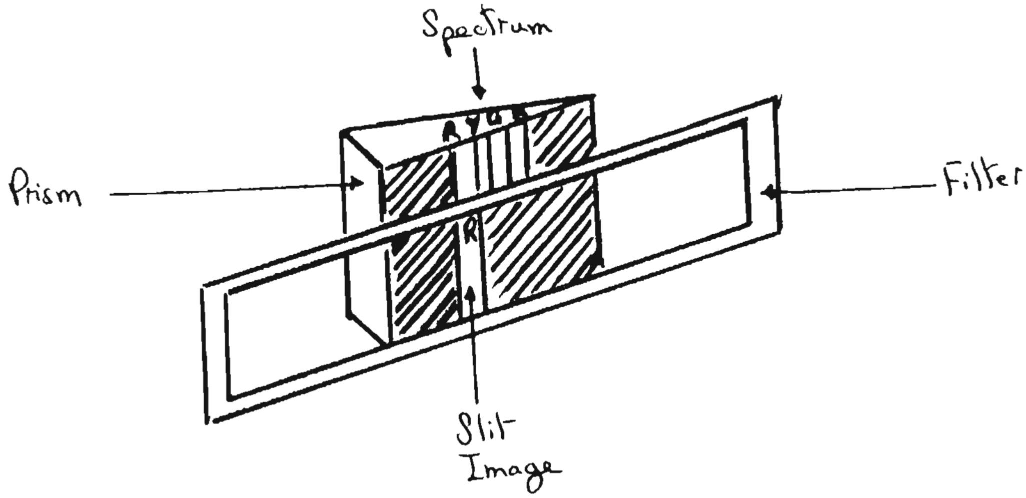
(iii) Repeating the experiments with daylight passing through a large cardboard slit is particularly interesting, since the scale of the set up is increased considerably. The distance between the source and prism is much greater, and it follows that the distance between the image and prism must be similarly increased, resulting in a wider separation of the colors in the image. In other words a much clearer and wider separation can be produced.

As the width of the slit increases white light appears in the middle of the spectrum leaving the edges colored. If you encourage the student he will probably guess that it is due to some form of overlapping of colors in the emergent ray. Don't present him with how this happens. Get him to sit down and draw a series of rays illustrating how they travel from the slit to the prism, to then be split up into individual colors. A few diagrams later many students will be able to work out for themselves how it is possible for emergent colored rays to overlap, creating white light as a result.



The narrower slit produces the best spectrum since very little overlapping of colors is possible, and it is such a spectrum that is observed prior to insertion of the red filter. Insertion of the filter causes the

slit image to appear much narrower. This is because only red light (R) is allowed to pass through the filter, the other colors such as Blue (B), Green (G) and Yellow (Y) being stopped.



Qualities of filters vary, and in fact one defines the color of a filter according to the light it allows to pass through. If the filter available allows some of the yellow region of the spectrum to be transmitted it is not a pure red filter. It is interesting to take different colors of cellophane to check their purity by this method.

You might mention to your students that the experiments which they have just performed are very similar to a series of experiments which Newton conducted with triangular prisms as far back as 1666.

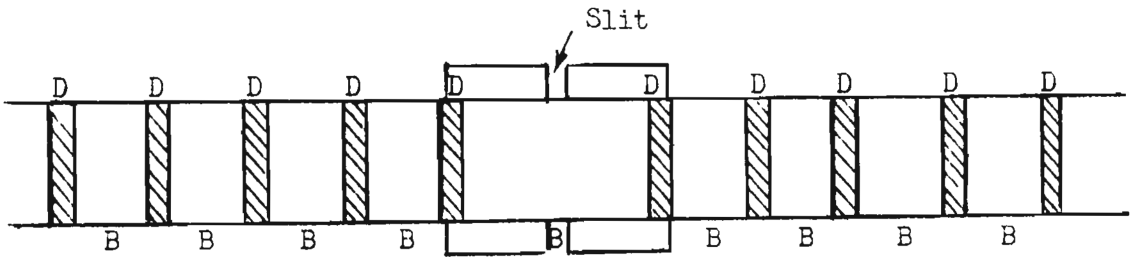
The main reason for introducing color at this stage is to avoid possible confusion in the observation of diffraction and interference phenomena which follow. There is therefore no particular need to discuss Newton's or Huyghen's explanations of color in terms of the Corpuscular or Wave Theories. However, for those concerned with an explanation Newton suggested that white light consisted of different types of corpuscles, corresponding to the different colors of light, and that these were affected differently on refraction. In other words, following the logic already developed for refraction of particles, he concluded that particles of blue light must travel at a greater velocity in a dense medium, such as plastic or glass, than particles of red light.

The Wave Theory agreed with the experimental observation that white light was composed of many colors, but it indicated that since blue light is refracted more than red light, that in a dense medium the velocity of blue light must be less than that of red light. Once again the two theories opposed one another on a question of velocity.

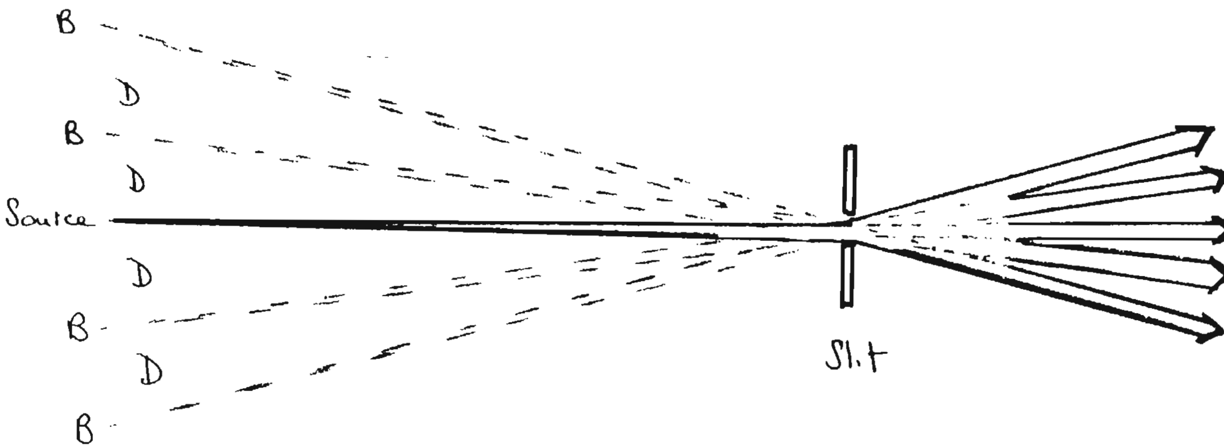
4.20 DIFFRACTION AND INTERFERENCE

4.21 Diffraction

(i) The pattern seen through the vertical slit, as one looks towards the vertical filament, is a series of dark (D) and bright (B) vertical bands (images). (Close inspection will show that the edges of the bands are



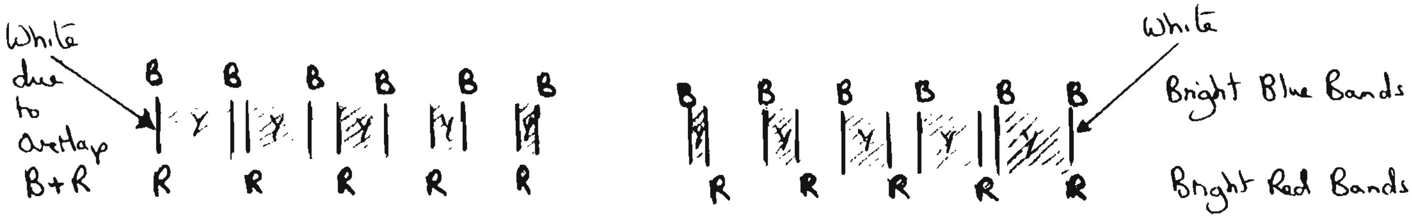
colored). The result will be a surprise to the student. However, the point that he should recognize is that effectively he has a series of bright images (B) of the slit, and these must be created by the bending of light rays in discrete packages, in the way illustrated below. The bending of the light



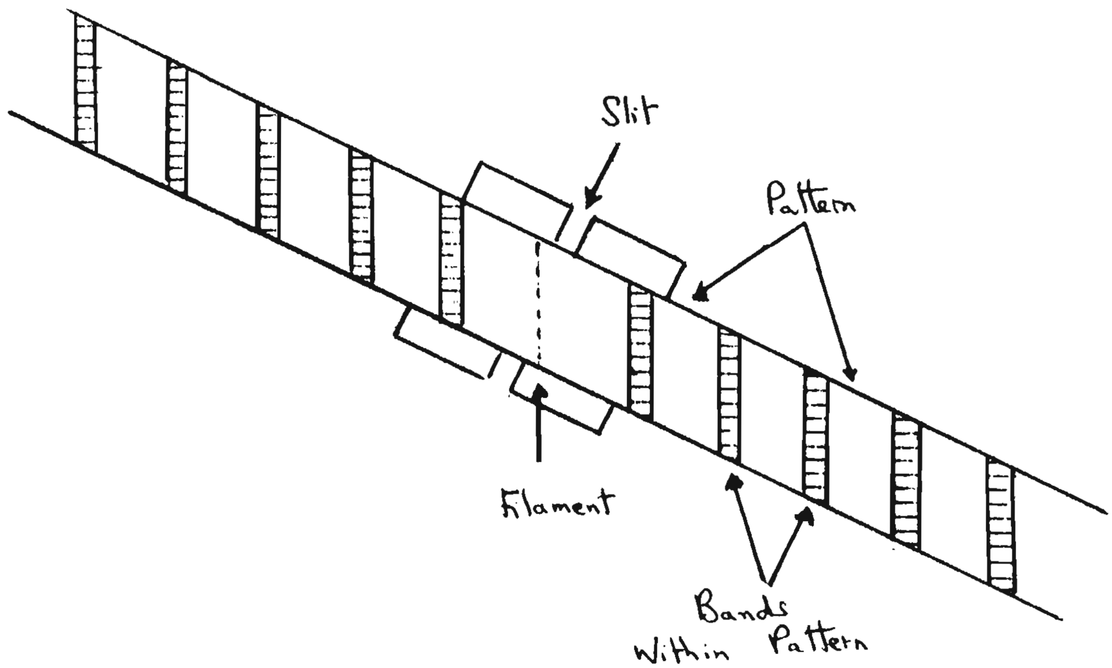
has not created a simple extended image of the filament, but effectively an extended image interrupted by a series of dark bands (D). Tell the student that this phenomenon will be investigated more carefully in a subsequent activity (Interference).

Apart from the inexplicable dark bands all the remaining observations tend to support the idea that light is behaving as a wave motion as it passes through the slit. Hence, as the slit is made narrower the bands become more widely separated, while conversely as the slit width increases the bands move closer and closer until they disappear. It is also noted that for a given slit width the separation of the bands increases as the distance between the filament and the slit increases.

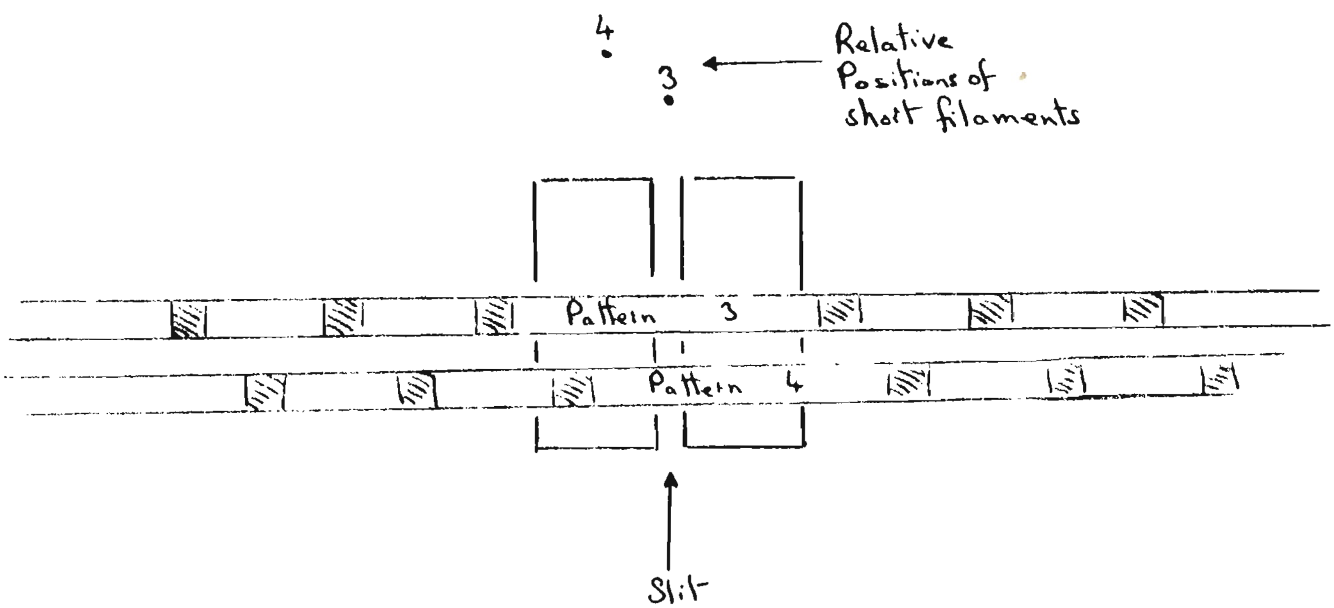
Close observation of the bright bands will show that the edges of the bands are colored. Using a red filter cuts out all other colors and not only increases the clarity of the bands, but also increases the number of bands that are visible. The explanation is simple. Different colored light rays are bent to differing extents. Each color on its own would produce a series of bright and dark bands. Superimposing the patterns one on top of the other for all the different colors would simply cause coloring of the edges of the bright bands near the center of the pattern, but towards the edges of the pattern there would be a regular overlapping of all colors of bright bands, thus eliminating the intervening dark bands and producing white light.



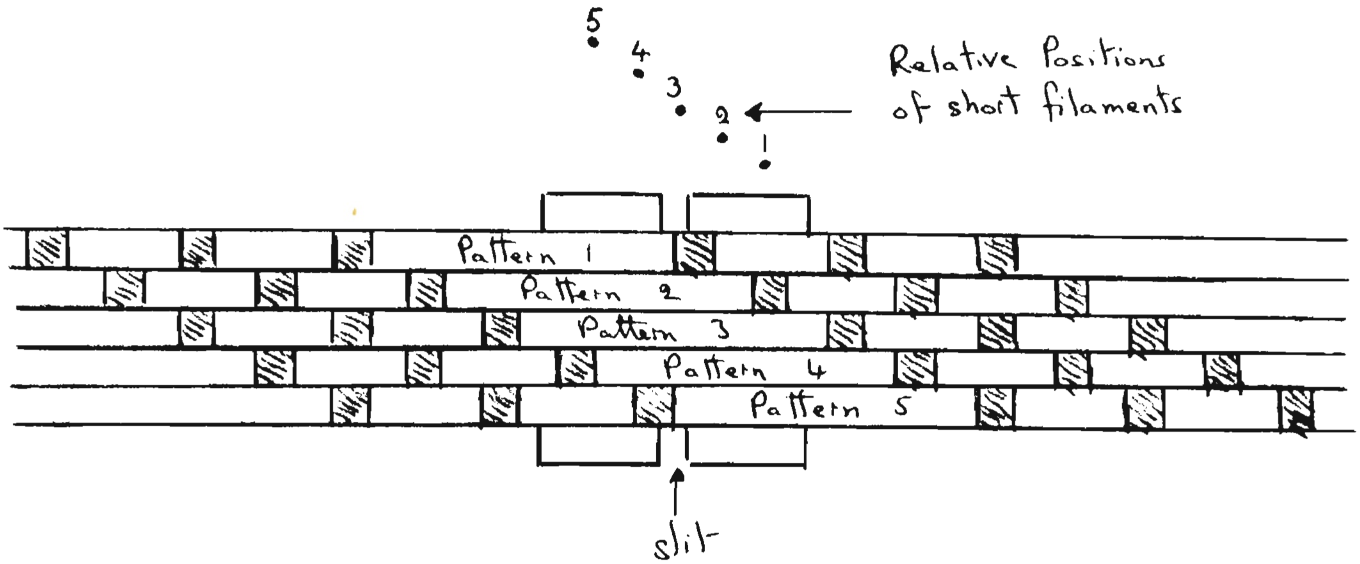
(ii) When the slit is rotated from its vertical position it is noted that the pattern rotates so as to spread out, on all occasions, at right angles to the edges of the slit. The banding within the pattern remains parallel to the filament.

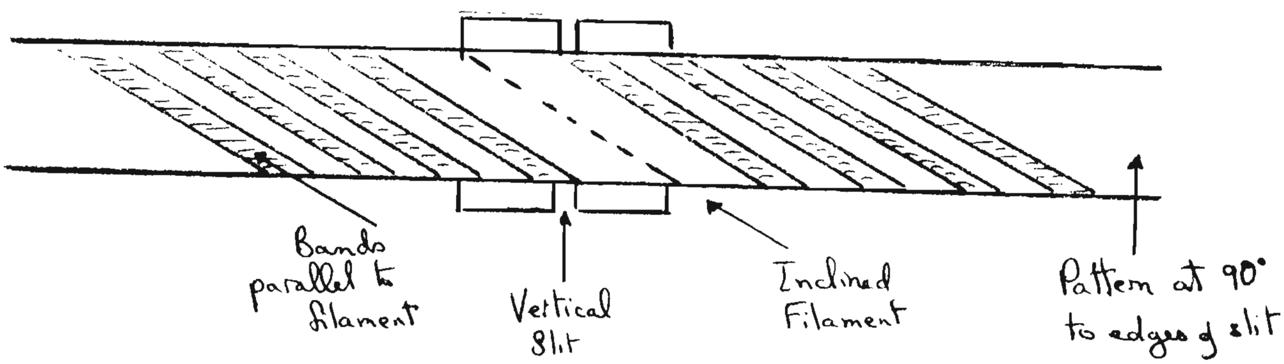


It is not too difficult to show that this behavior can be predicted from the first observations of diffraction bands. Draw a diagram illustrating how the bands spread out from a short vertical filament (position 3) when light passes through a vertical slit. Then keeping the slit in the same position illustrate what happens if the position of the source is moved slightly downwards, and slightly to one side (position 4).

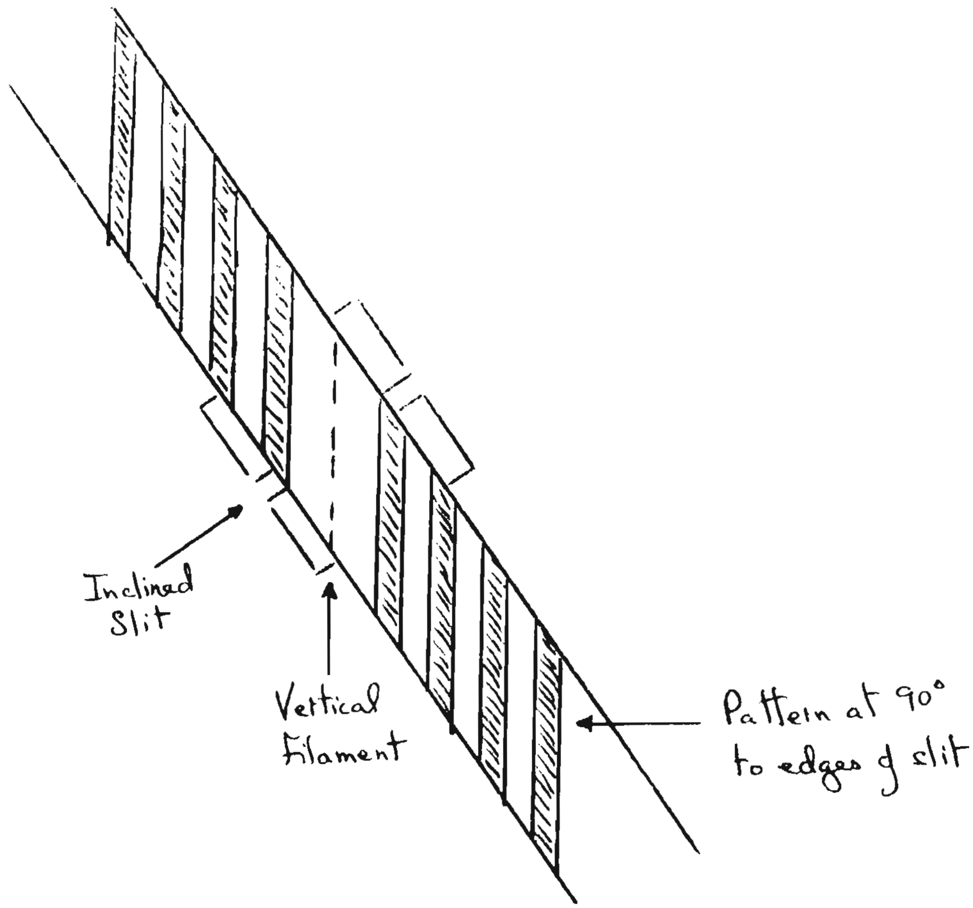


It is a very short step from this to determining what sort of pattern would be produced if 5 short filaments, in positions 1 to 5, were joined together into one long filament, inclined at an angle to the vertical.



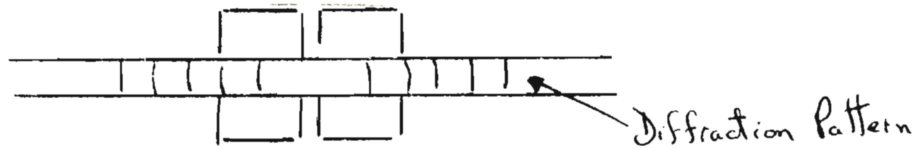


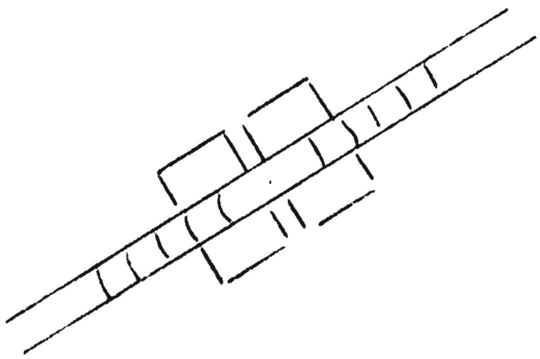
It is equally simple to consider what would happen if the whole setting was rotated so that the filament was vertical and the slit inclined. The result is the type of pattern observed by the student.



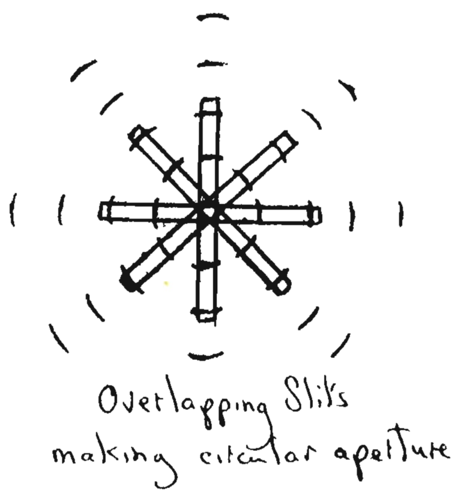
The reason for the theoretical explanation is simply to show that the pattern observed with an inclined slit is of precisely the same nature as that with a vertical slit, and can in fact be predicted theoretically.

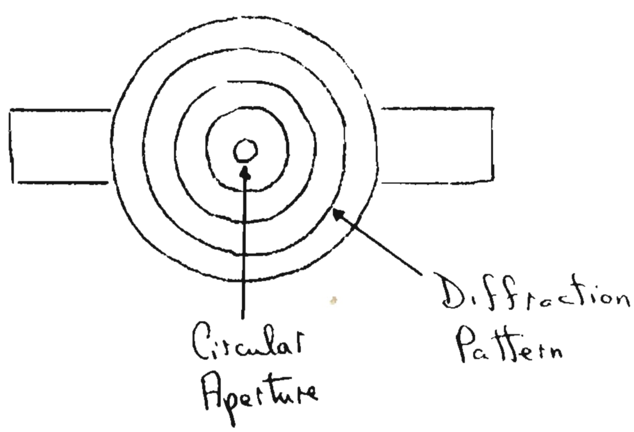
(iii) Using a point source and a vertical slit the diffraction pattern is very similar to those already observed, spreading out at right angles to the edges of the slit. The major difference is that since the source is circular, rather than a line, the bands are always parallel to the edges of the source, and hence to the edges of the slit.





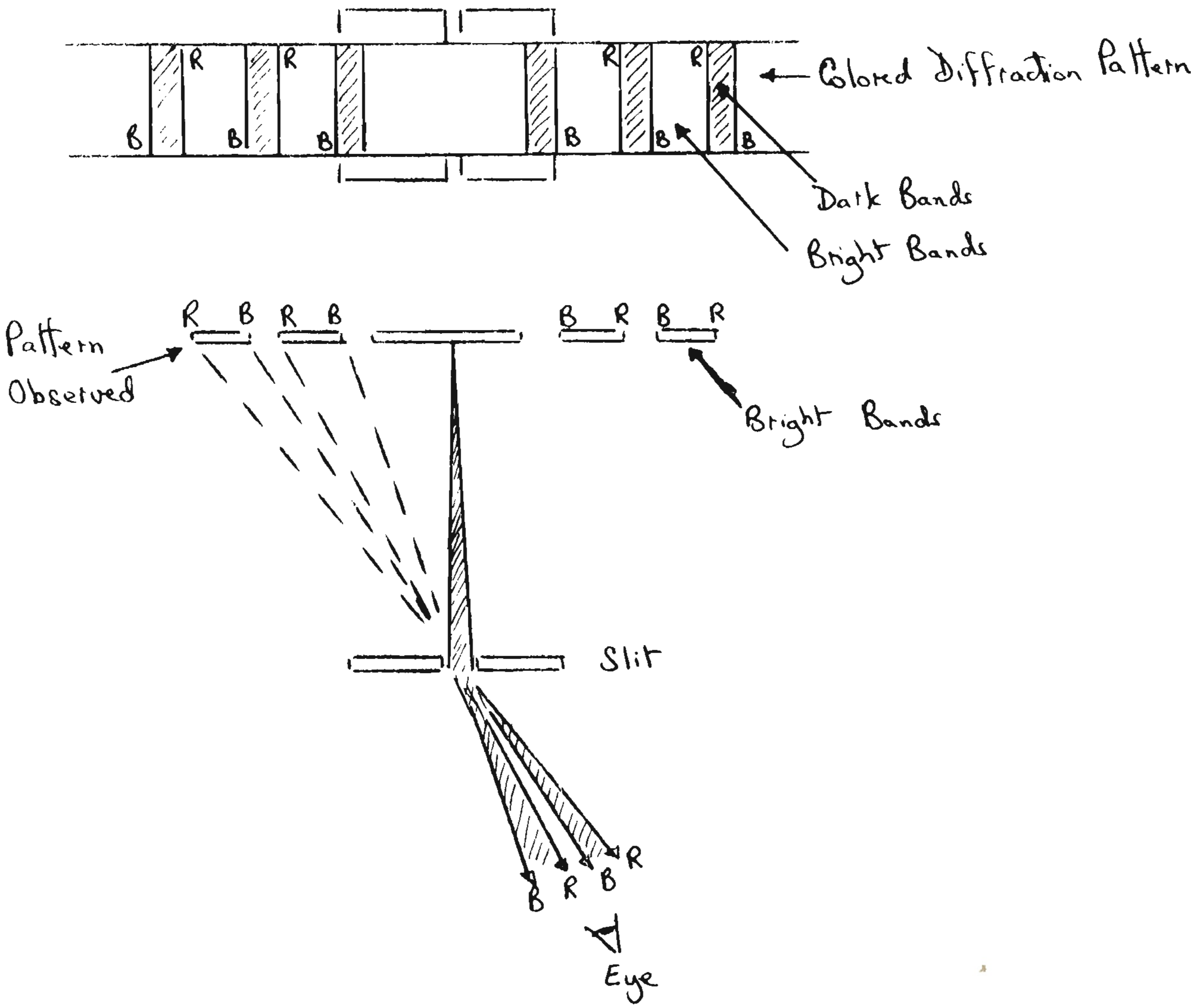
If you point out to the student that he could produce a circular aperture from a series of overlapping slits he will probably be able to predict that a circular aperture will produce circular diffraction bands.





The main point for the student to grasp is that the diffraction patterns he observes with apertures are of precisely the same basic form as those which he has observed with narrow slits.

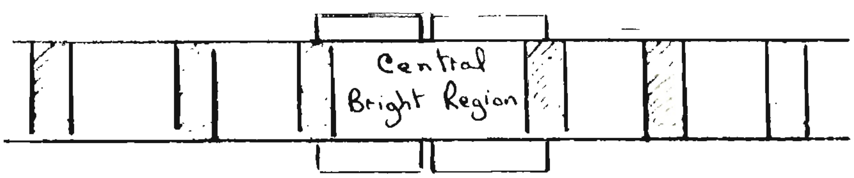
The advantage of repeating the experiments outdoors on a larger scale is that the patterns are magnified considerably. In particular the color of the bands can easily be distinguished, and it is noted that within any bright band the red light is bent more than the blue (the opposite to that which occurs with refraction).



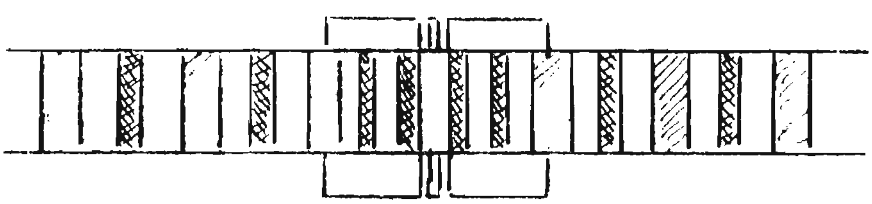
4.22 Interference

With two equal slits placed side by side a pattern very similar to the diffraction pattern of a single slit is produced. It appears that the individual diffraction patterns from the two slits are so close together that they superimpose one on top of the other, appearing as a single pattern. Covering one of the slits still leaves the diffraction pattern of one slit in the same position.

However, there is one major difference between the pattern from one slit and that from two slits, and this is seen clearly if a red filter is used to eliminate the overlapping of colored patterns which result in the formation of white light. It will be seen that with one slit the central bright region of the diffraction pattern is of uniform intensity. The remaining bright bands are not as bright, but are also uniformly illuminated. However, with two parallel slits regular banding is created within the uniformly bright areas. This may not be so clear in the outer areas, but in the central region the intensity of illumination is sufficiently bright to enable these new bands (interference bands) to stand out clearly. As soon as one of the slits is covered the interference pattern disappears, leaving the diffraction pattern of the slit upon which the interference bands were superimposed.



Bands due to Diffraction at Single Slit



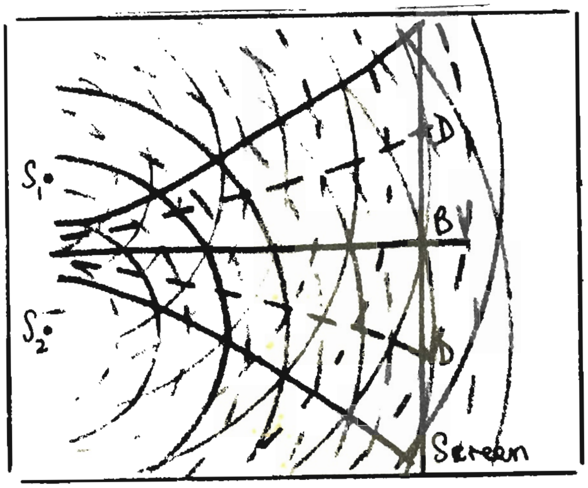
Bands due to Interference of two slits superimposed on Diffraction Pattern of Single Slit.

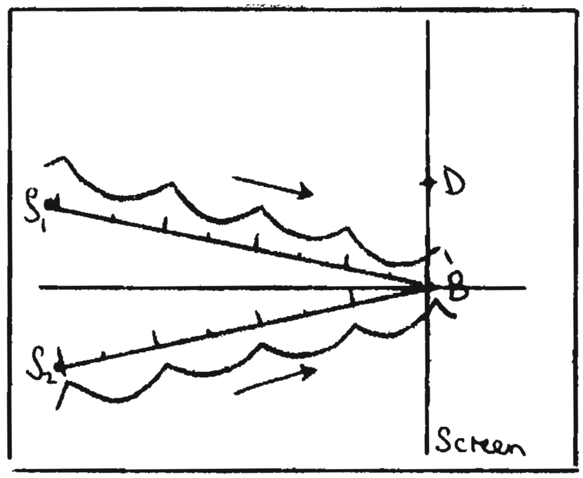
It would seem fairly logical for students to assume that the new banding is due to the interference of the two light motions from the adjacent slits. It would also seem fairly logical to suggest that the bright and dark bands created within a pattern from a single slit is due

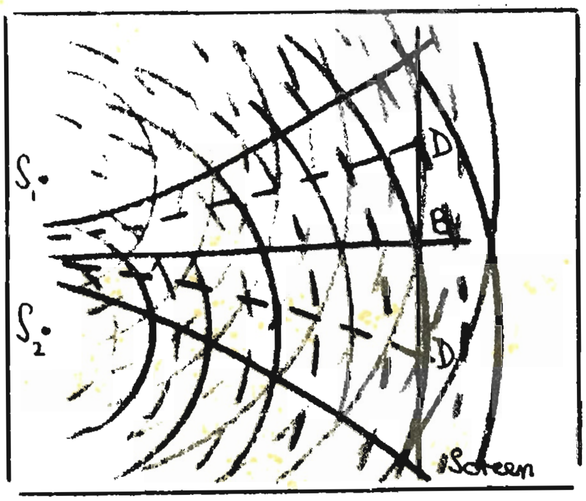
to some form of interference effect, probably due to each point within a single slit being capable of acting as a point source and thus interfering with the light generated from the adjoining point sources within the same slit.

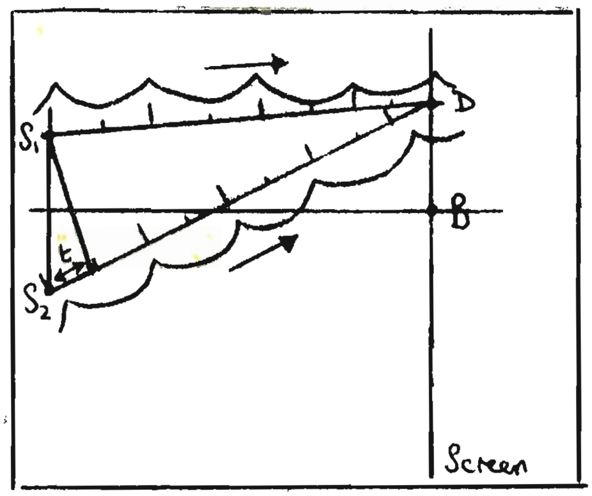
The majority of students will be happy to leave the discussion of interference and diffraction at this point, and it would seem that there is no need to bore students with more detailed theory. However, for teachers with particularly bright students who may wish to discuss some of the more specific aspects of the Wave Theory further, the following review may prove to be useful.

The diagrams overleaf represent waves generated from two identical sources of light (S_1 and S_2) such that they interfere with one another. A screen placed in the path of the waves picks up the pattern of bright and dark bands, and it follows from the diagrams that points D and B must correspond respectively to dark and bright bands of light. The same conclusion can be achieved more rapidly by following the diagrams on the right. Thus the lines S_1B and S_2B represent the directions of the two individual wave motions towards the point B. Representing the troughs and crests of the two motions along these lines it becomes clear that, if the motions travel equal distances to point B, crests of the two motions will arrive at the point simultaneously. B must therefore correspond to a point of maximum disturbance, and hence to a bright band. Similar consideration of the point D will show that the paths S_1D and S_2D differ by a distance (t) equivalent to half a wavelength. It therefore follows that the motion from S_2 will be half a wavelength behind that from S_1, when both reach D. In other words a crest and trough will arrive simultaneously at D from the two sources resulting in zero disturbance at the point. D must therefore correspond to a point of zero disturbance, or a dark band. The same logic indicates that the screen must be covered by a succession of dark (D) and bright (B) bands alternating one after the other.









————————	Wave Crests
— — — —	Wave Troughs
━━━━━━━━	Interference Maxima
━ ━ ━ ━	Interference Minima

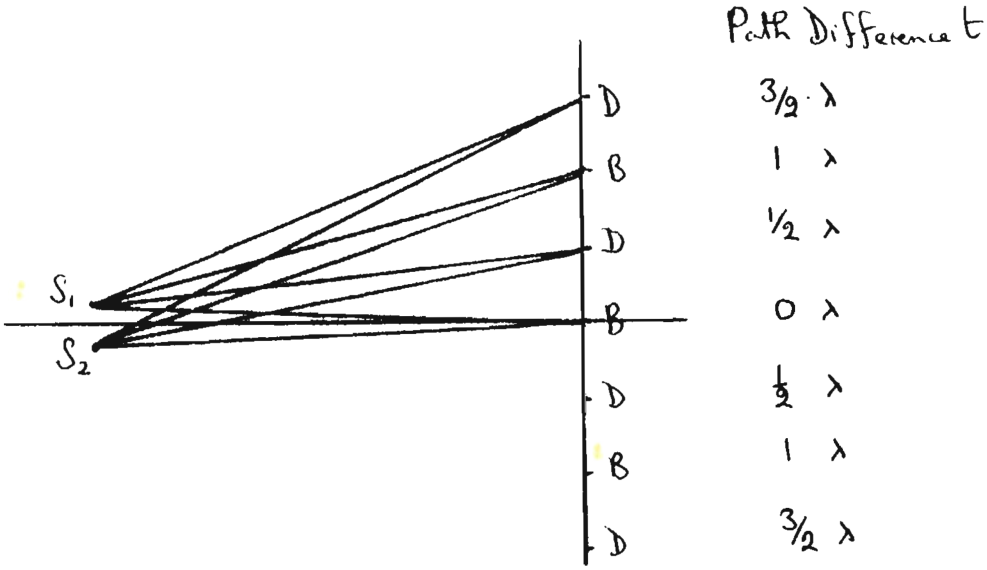
D = Point of Destructive Interference

B = Point of Constructive Interference

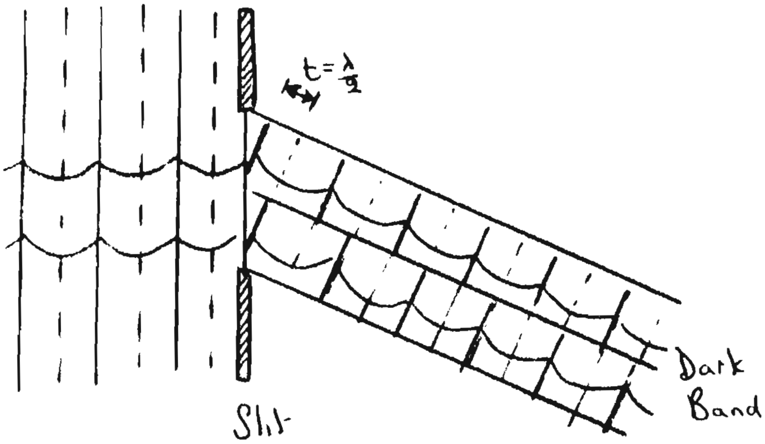
S = Source of Wave Motion

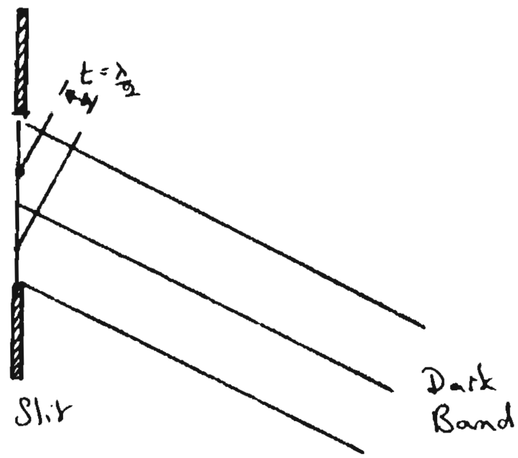
d = Distance between sources

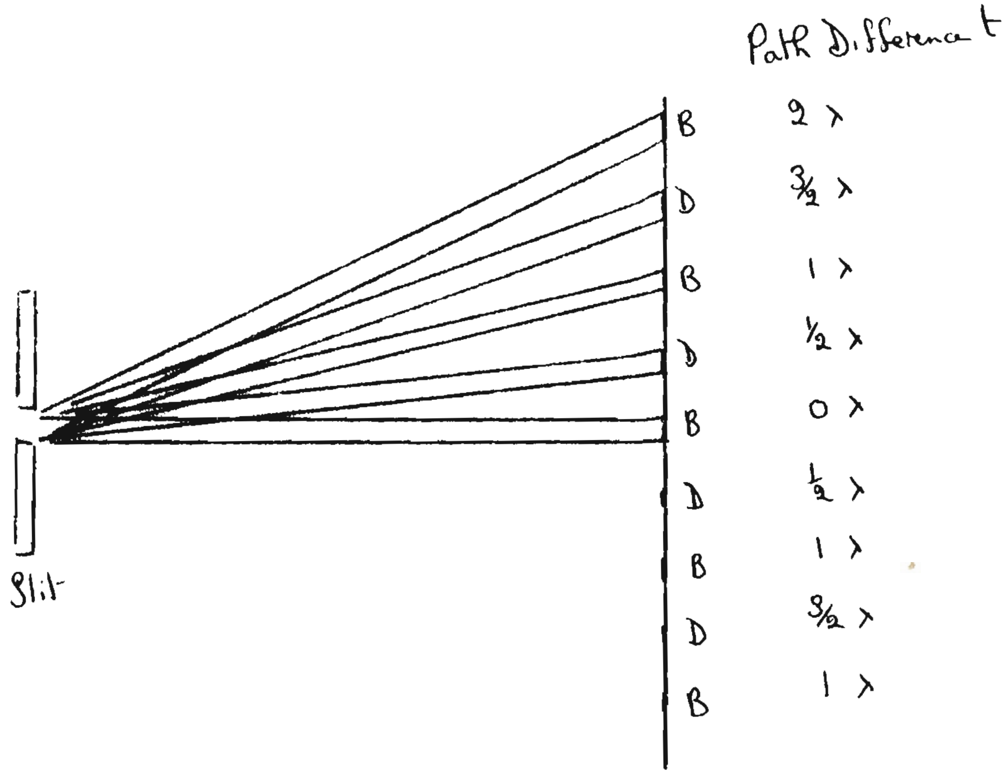
t = Difference in paths travelled ($S_2D - S_1D$)



The dark and bright bands created by a single slit on its own are created by a very similar interference effect. Instead of having two sources which interfere with one another we might consider the light passing through the slit as consisting of two parallel halves which are able to interfere with one another, according to the path difference (t) created between the two halves. The logic is otherwise the same as for the interference produced by the two sources above (see diagrams overleaf).


t = λ/2
Dark Band
Slit


t = λ/2
Dark Band
Slit

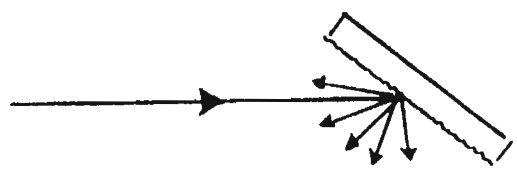

Path Difference t
B 2 λ
D 3/2 λ
B 1 λ
D 1/2 λ
B 0 λ
D 1/2 λ
B 1 λ
D 3/2 λ
B 1 λ
Slit

4.30 FURTHER OPTICAL PHENOMENA

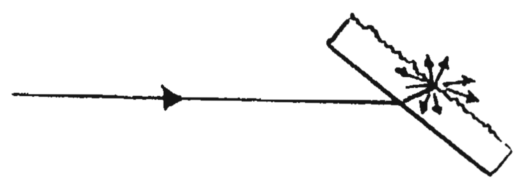
4.31 Scattering of Light

(i) In previous activities we have noted that when a ray of light strikes a surface the reflected ray leaves the surface at the same angle as that at which the incident ray strikes it. This is true even when the surface is curved, so long as we only consider the limited surface struck by the ray. It is this form of behavior which gives rise to the creation of images in plane and curved surfaces.

When light is reflected from a rough surface it scatters in all directions. There is no single point from which the light appears to emerge and we therefore would not expect to see an image created by reflection. This is confirmed when light is allowed to fall on the roughened surface of the plastic prism. The scattering of light is clearly seen, and no image is produced.

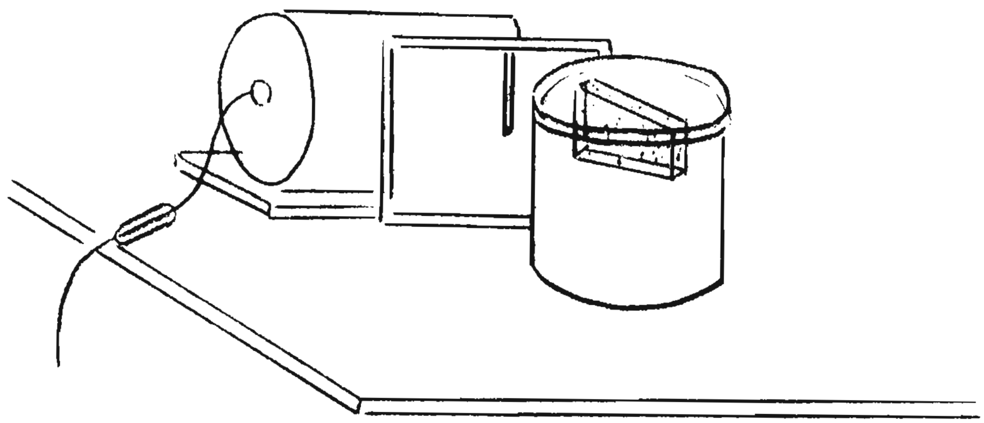


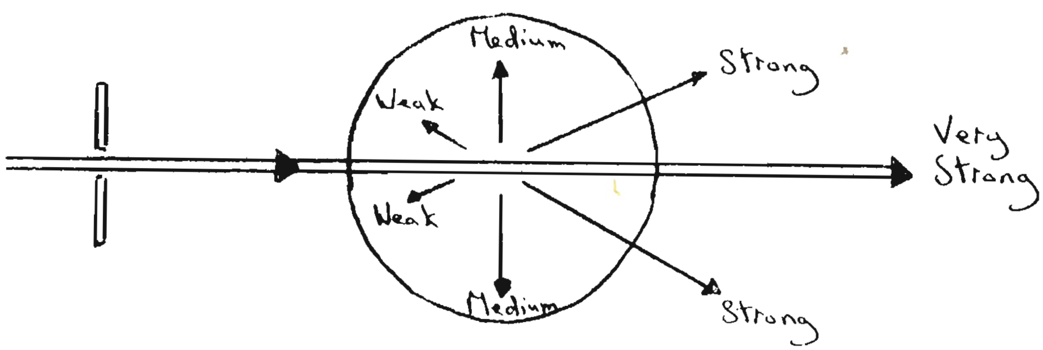
In the same way when light is transmitted through a plastic prism so that it emerges from a roughened surface we anticipate that light will be scattered in all directions, and therefore that no clear image of the source will be seen. In practice sufficient light is scattered to prevent the distinct formation of an image, even though some light tends to still be transmitted in a preferred direction. The experiment tends to be more convincing if a piece of paper is stuck over the roughened surface, as this has greater scattering power.



It is this property of scattering of light which enables us to trace rays through plastic prisms. When a ray of light passes through a prism its passage is invisible to the eye unless the surface of the prism, in contact with the table top, is roughened. This causes scattering of the light ray in contact with the rough surface, and it is such scattered rays that reach the eye above the prism. If no light is scattered upwards from the ray, no light would reach the eye from the ray, and the latter would not be seen.

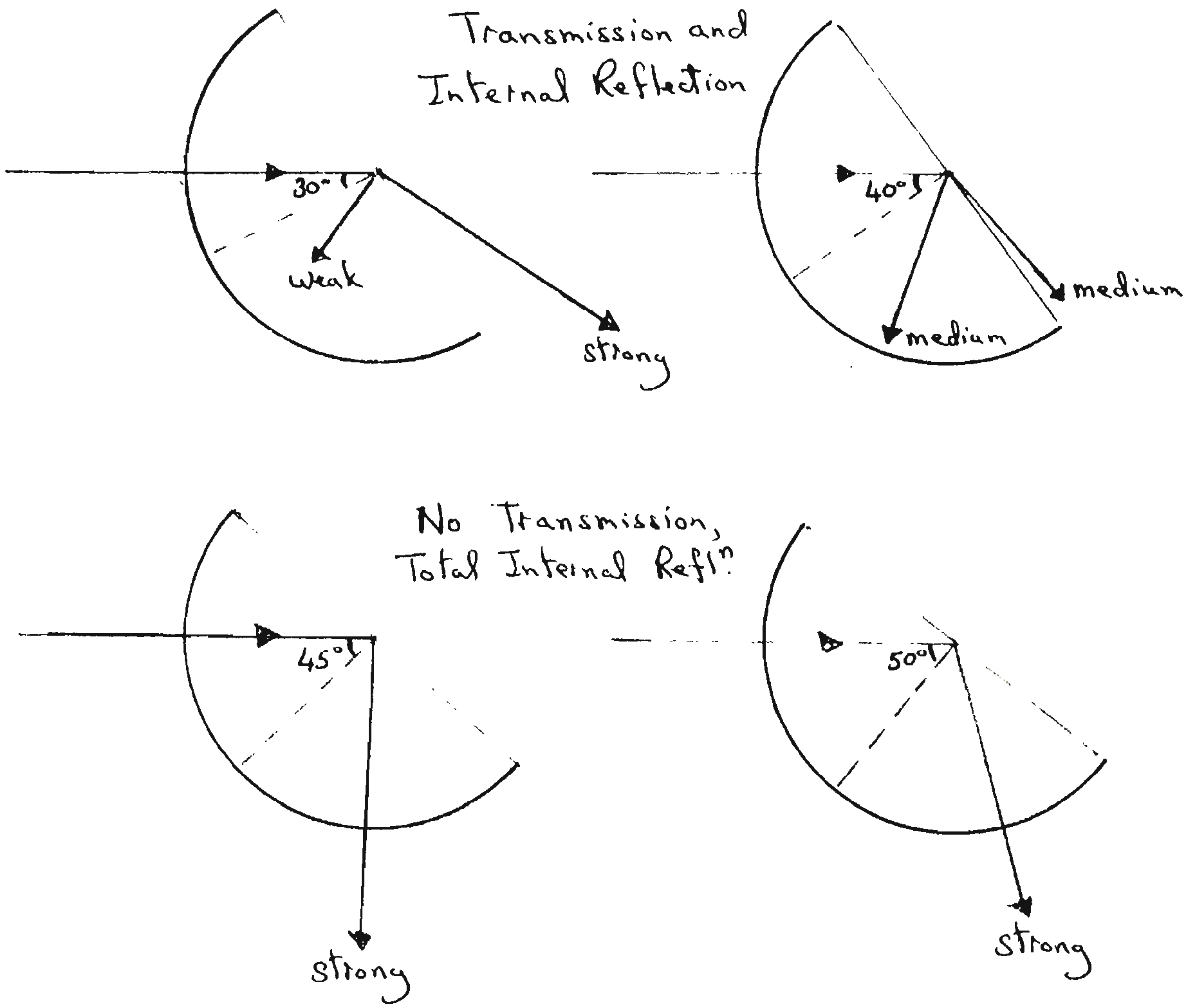
(ii) This experiment is interesting in that it shows how smoke particles are able to scatter light. The ray of light is no longer traced by a bright line on the table, but by a 3 dimensional picture of the ray as it passes through the smoke. The picture tends to be clearest when viewed from an end-on position, since the scattered rays tend to be most concentrated in that direction.





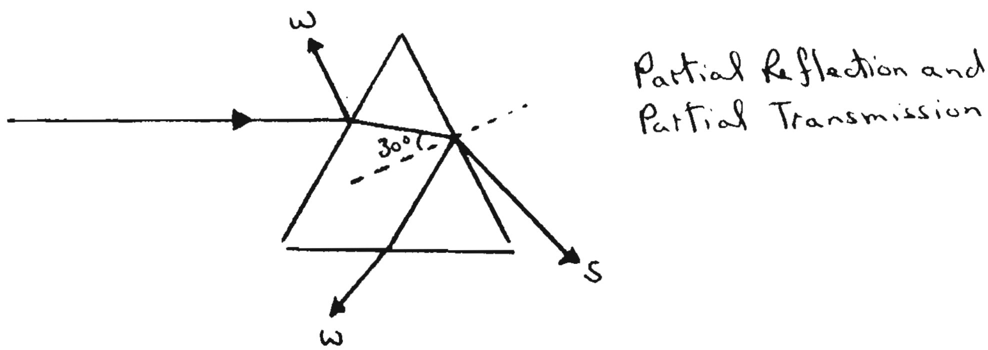
4.32 Total Internal Reflection

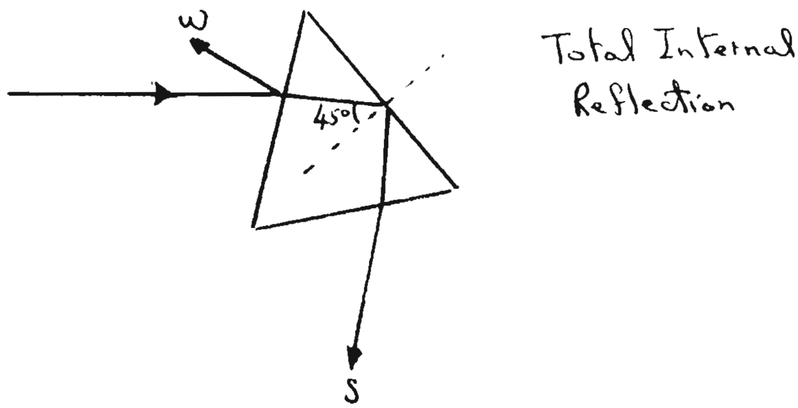
(i) It is noted that with the angle (θ) of the order of 30^{o} or less that virtually no internal reflection is visible, and the transmitted light is strong. As the angle (θ) increases the intensity of the internally reflected ray increases until somewhere between 40 and 45 degrees, at which point the transmitted ray disappears and total internal reflection occurs.



It seems that light cannot strike a plastic-air interface, at an angle (θ) greater than about 40^{o} if it is to cross the boundary into air. The angle (θ_c) at which this limit occurs is known as the Critical Angle of the prism.

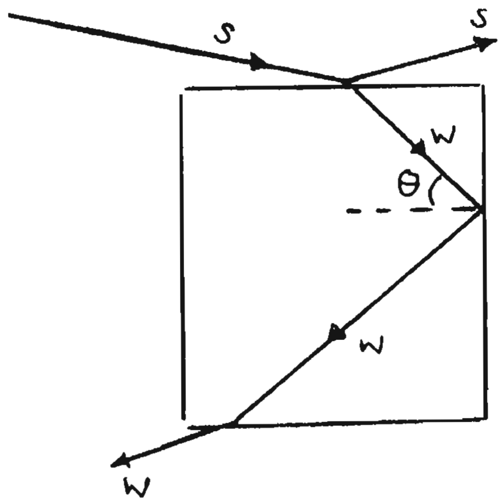
(ii) A set of observations similar to those of the foregoing experiment may be obtained with the triangular plastic prism. It will be found that if the light transmitted through the prism approaches the plastic-air interface at an angle (Θ) less than 40° it will be transmitted across the surface into the air, but if it approaches the surface at an angle greater than this it will be totally internally reflected. It also becomes clear that the





Critical Angle for the triangular prism is the same as that for the semi-circular prism. The Critical Angle is in fact dependent on the material of the prism and not on its shape.

(iii) Laying the rectangular plastic prism horizontally on the table top it is found impossible to make a ray of light pass into the prism at one surface and out through the adjacent surface. On measuring the angle (θ) with which the ray approaches the plastic-air interface it is noted that this is always greater than 42^o, the Critical Angle for the plastic, and it follows that total internal reflection must always occur at the second surface.



(iv) The above explanation also explains the observations in this activity. Light rays can be transmitted from the marks beneath the prism to the eye, after internal reflection at the vertical side. The marks are therefore readily seen by the eye, even though the observer is not looking vertically downwards into the prism.

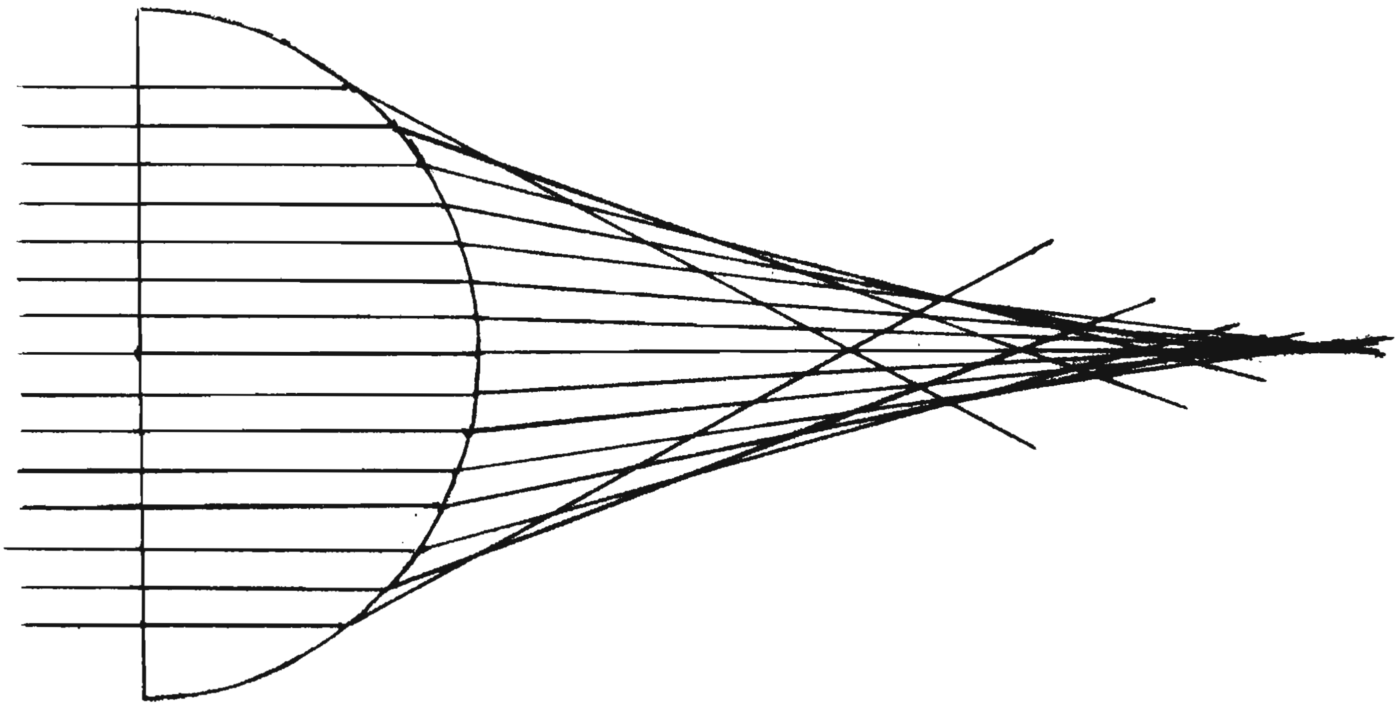
The pencil, however, cannot be seen, for we have already seen that it is impossible for light rays to enter the vertical side from the pencil and emerge from the adjacent top surface of the prism to the eye.

When the pencil is pressed close to the vertical side it is as though the pencil becomes a part of the prism, for the rays from the pencil are transmitted through the prism to the eye.

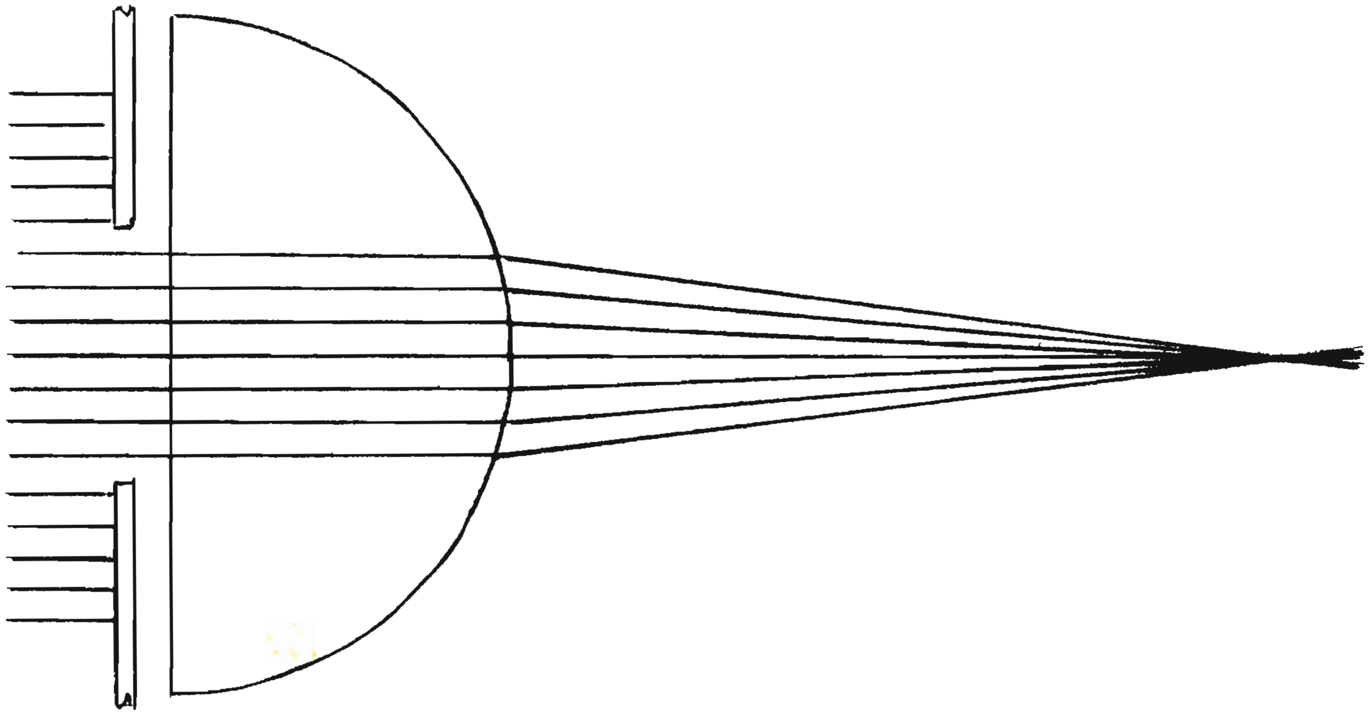
Placing a finger against the vertical side, the ridges of the finger prints are close enough to the side to be seen through the top surface but not the hollows between the ridges, which therefore appear a silvery white, due to light internally reflected, via this side to the eye, from the bottom surface of the prism.

4.33 Refraction by Lenses

(i) The light rays reaching the multiple slit are almost parallel to one another, and they strike the plane surface of the semi-circular prism at approximately 90 degrees. There is therefore very little refraction until the rays cross the curved surface of the prism when the rays are bent inwards beyond the prism.

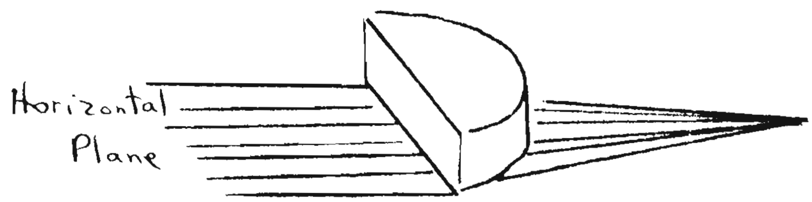


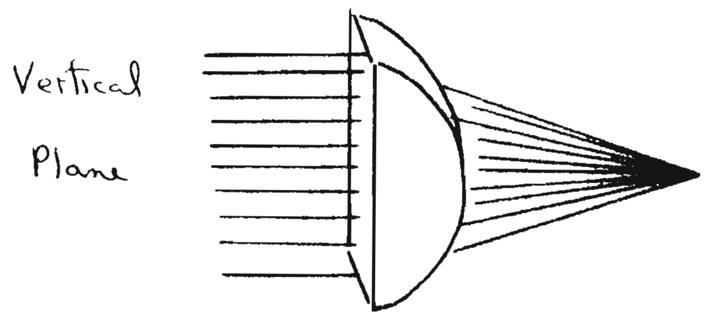
When the outer rays are eliminated by means of screens it is noted that the inner rays all intersect at the same point. The same sort of behavior is noted regardless of whether the plane surface or curved surface is nearest to the light source, and regardless of whether the source is moved nearer to, or further away from, the prism.



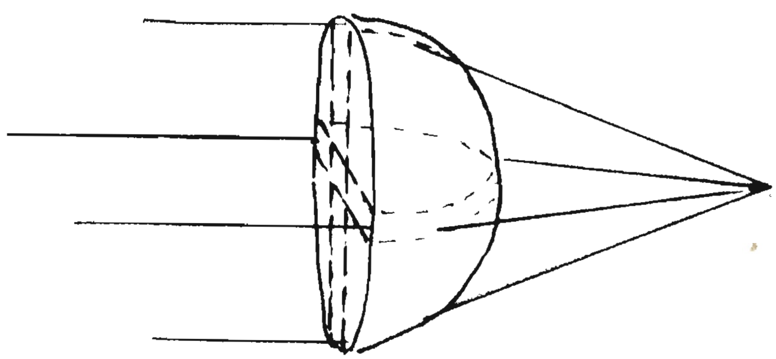
It is well worthwhile taking a little time to discuss with students why we would expect lenses to behave in a very similar way to the semi-circular prism. Point out that the prism is curved in 2 dimensions (a plane) only, while a lens is curved in 3 dimensions. Therefore just as the semi-circular prism will bring rays in 2 dimensions to a point focus, so a lens will bring rays in 3 dimensions to a point focus.

You might simplify this for the student by pointing out that the prism has shown us how the rays are affected in a horizontal plane, and if we rotated the light source, multiple slit and prism through 90 degrees about a horizontal axis we would expect precisely the same behavior, but in a vertical plane.

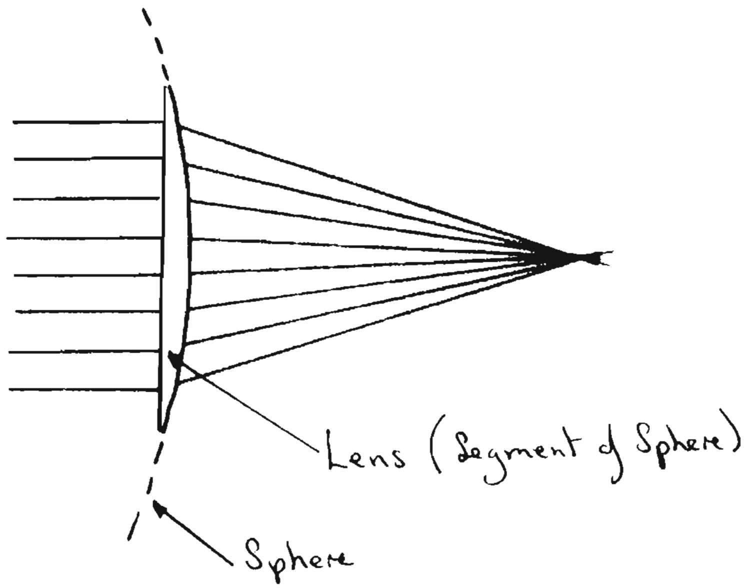




Point out that a lens is really a combination of the prism in both a horizontal and vertical plane (imagine the semi-circular prism rotating about a horizontal axis) and we might therefore expect a lens to affect rays in 3 dimensions in just the same way that the semi-circular prism affected rays in 2 dimensions.



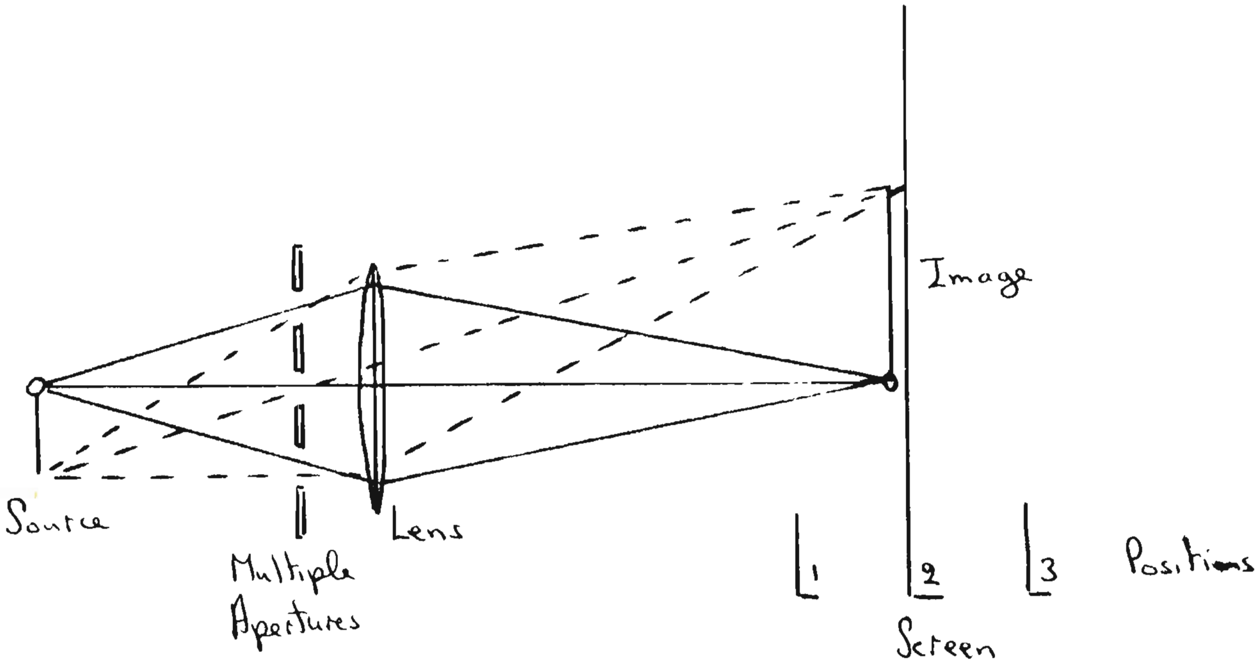
Experimentation with the semi-circular prism shows that rays are only focused to a point focus if a segment of the semi-circle is actually used in the bending of rays. The same logic shows that a lens which is to focus rays to a point focus must be a segment of a sphere, not a whole hemisphere.



(ii) Light passing through the pinhole aperture in the lid of the lamphousing creates an image of the filament on the screen. Using the pencil to block out different parts of the filament it is seen that light from the bottom of the filament goes to the top of the image, and from the top of the filament to the bottom of the image. In other words the image is upside down.

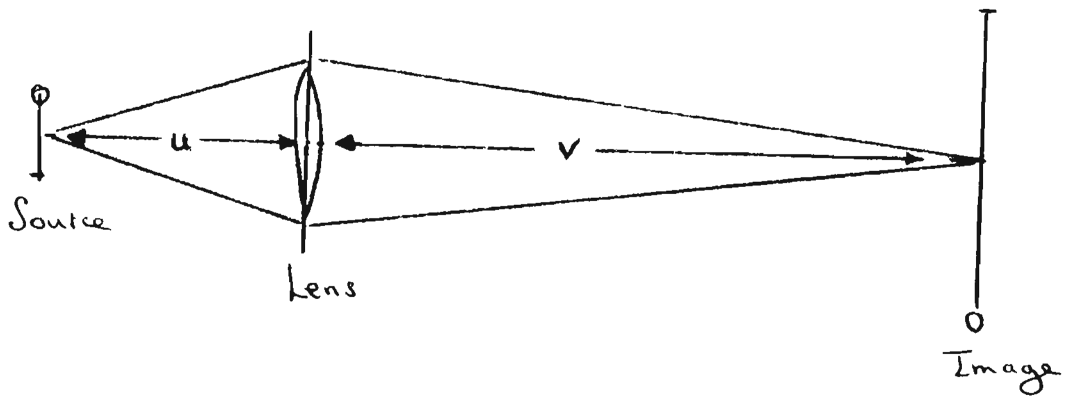
This is to be expected since only small rays of light from the filament can pass through the aperture. From each point on the filament we might say that only one small ray manages to pass through the aperture to the screen. Since light travels in straight lines the light from the bottom of the filament will travel towards the top of the screen while that from the top of the filament will travel towards the bottom of the screen. The same logic explains why the right side of the image corresponds to the left side of the filament.

(iii) When the single aperture is replaced by the apertures of the slit/aperture combination 9 images of the filament are produced on the screen. Placing the lens between the apertures and the screen it is possible to make all 9 images overlap into one image. This is not too surprising when we recall that lenses have the property of bringing rays together to focus at a single point. The diagram below illustrates how this is achieved.



It follows from the diagram that if the screen is placed in position 2, a single image will be created on the screen, whereas in positions 1 or 2 multiple images will be created, and this is, in fact, what is observed.

What is probably more surprising to the student is that, with the screen and filament in a fixed position, there are two positions of the lens which create sharp single images on the screen. This is explained simply by the fact that if rays were transmitted to the lens from the image position, you would expect them to retrace the original paths to the position of the source. In other words light rays after travelling a distance 'u' from the source to the lens may be focused to an image after travelling a further distance 'v' to the screen. Equally well they could travel a distance 'v' from source to lens, and be focused after travelling a further distance 'u' from lens to screen.



If a sharp image is created by placing the lens at a suitable distance behind the apertures, it is found that removing the apertures does not affect the sharpness of the image. This is not too surprising, for the apertures simply limit the number of rays striking the lens. Without the apertures the rays still travel towards the lens in the same way as before, and are refracted in an identical manner.

(iv) Setting up the lens between source and screen it is found that as the object distance 'u' increases the image distance 'v' decreases. However, as the object distance continues to increase from 50 to 70 cms the decrease in the image distance is far less than expected, and when the object distance is increased even further to a meter it is found that the image distance remains constant at about 8.5 cms. Even with the window as a source of light, and the object distance of the order of 4 or 5 meters, the image distance remains the same (8.5 cms). This fixed image distance indicates the strength of the lens used, and we refer to this distance as the focal length of the lens.

Once the object distance reaches 70 cms it will be found that the rays falling on the lens are virtually parallel. With greater object distances the rays will still be parallel. The lens has a definite bending power and will always affect parallel rays in the same way. It is therefore not too surprising to find that for object distances of 70 cms or more the corresponding image distance remains constant.

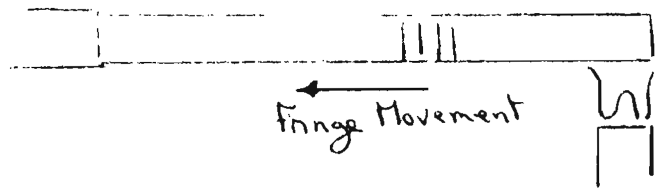
4.34 Formation of Interference Colors

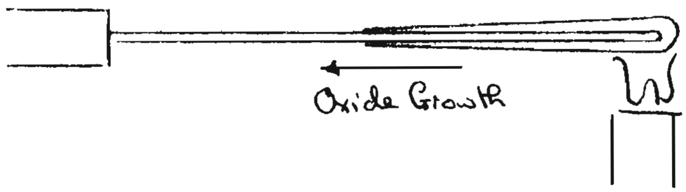
(i) Olive oil will be noted to be a transparent, pale yellow liquid. When a drop is added to the surface of the water in the ripple tank it spreads out rapidly, forming a thin circular film of oil. Circular colored fringes appear almost immediately near the perimeter of the oil film, and these increase in diameter as the film expands outwards.

Students should be able to repeat this two or three times, by which time the water surface will be so contaminated with oil that further drops will no longer spread out on the water surface, remaining instead as small, almost colorless, globules. This would suggest that the colored fringes produced are not the result of chemical action with the water, but somehow related to the thickness of the film.

(ii) The fringes observed with the soap film are almost identical. As the film drains downwards a simple soap solution wedge is created, with the fringes moving downwards at the same time, the positions being dictated by definite thicknesses of film. It is interesting to note that the light transmitted through the film will cause interference fringes in much the same way as that reflected by the film. The fringes disappear in the top region as it becomes very thin and also disappear in the lower region as the film becomes too thick.

(iii) Fringes will be seen to form on the metal surface, moving along the strip away from the flame. This is due to the formation of a thin oxide layer on the surface of the metal, which grows outwards from the end in contact with the flame. The oxide layer forms into a wedge shaped film, being thickest nearest to the flame. Reflection of light occurs at the upper and lower surfaces of the oxide layer in just the same way as with oil films or soap films. As the oxide film grows along the metal surface, the fringes move in the same direction.





This is a nice method of testing whether metals are likely to corrode easily. Rapid formation of interference fringes indicates ease of oxidation, and possibly ease of corrosion. The two strips provided oxidize readily.

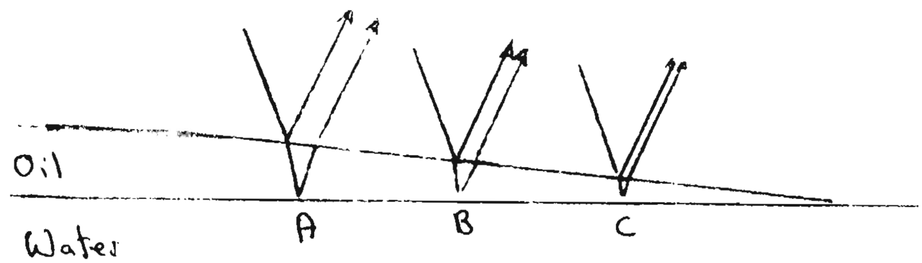
The purpose of this section is to let students see other interference phenomena, mainly in thin films. So long as students are reasonably convinced that the phenomena observed are probably caused by interference there is no need to take the discussion further. There is no intention that these simple experiments should be extended into a full treatment of thin film interference.

In all the three above activities light is reflected from the upper and lower surfaces of thin films (oil film, soap film, oxide film), and it is the two reflected wave motions which superimpose one on top of the other to create interference patterns.

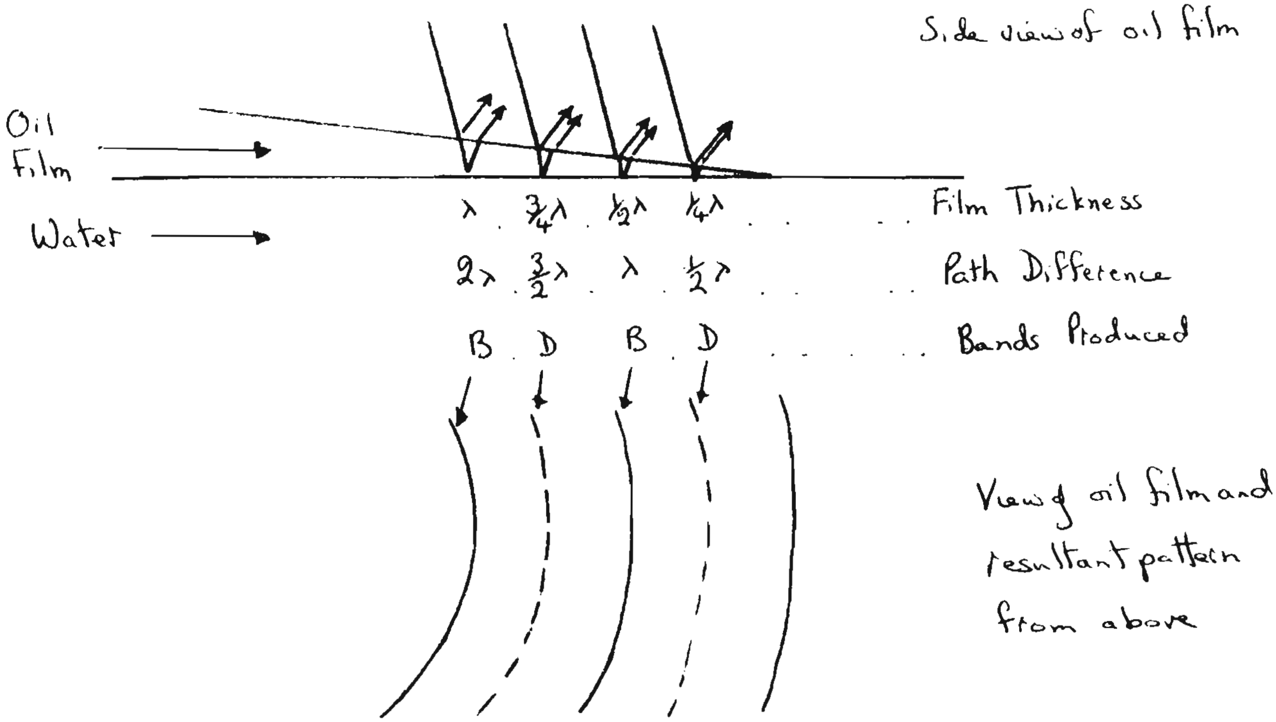
If the two surfaces of the film are too far apart (A) the reflected rays are too far apart to superimpose on one another, to create interference patterns. If, however, the surfaces are close together (B) so are the reflected rays, and interference becomes possible. However, it will be noticed that the interference fringes produced spread out widely into spectral colors. As soon as such colors begin to overlap white

light is produced, and no further fringes are visible, even though the reflected rays may be close enough together to interfere with one another. There is thus a very limited region (C) where the film is sufficiently thin for colored fringes to be observed without overlapping to produce white light.

The success of the oil film in producing interference fringes lies in the fact that it becomes so thin on spreading out that there is a relatively large region (C) in which colored fringes are possible.



Interference fringes are produced in thin oil films since the ray reflected from the lower oil surface travels further than that reflected from the upper surface. The path difference between the rays is almost equal to twice the width of the oil film at the point under consideration. If the film thickness, at the point in question is equal to a quarter of a wavelength, we would expect to find a dark interference band. If the film thickness is a half wavelength the path difference is a whole wavelength, and we would expect a bright band. From a broad light source, such as the sky, we would expect bright (B) and dark (D) bands to be created as indicated in the diagram overleaf. Remembering that different colors of light have different wavelengths, it would follow that colored fringes would be produced at different film thickness.


Side view of oil film
Oil Film
Water
λ 3/4λ 1/2λ 1/4λ
Film Thickness
2λ 3/2λ λ 1/2λ
Path Difference
B D B D
Bands Produced
View of oil film and resultant pattern from above

5. ELECTRICITY

5.10 ELECTROMAGNETISM

5.11 Magnetic Effects of an Electric Current

Magnetic phenomena are introduced to the student in such a way that electricity is seen to be the primary cause of such phenomena. It would be wrong to introduce this topic to the student with an initial lecture on the "Facts of Electricity", for a picture of the nature of electricity will emerge gradually as a side product of the observations.

(i) It is quite sufficient for the student at this stage to set up a simple electrical circuit containing a dry cell and bulb, and to recognize that a dry cell has a special property which is capable of producing a lighting effect in the bulb. This property we label electricity, and investigate more thoroughly at a later stage.

Before students perform the proposed experiments it is advisable to check whether the hard and soft iron cores to be used have retained any magnetism from previous experiments. Any residual magnetism should be removed by means of the demagnetizing coil. Should it be considered desirable to remove residual magnetism from the small pieces of steel wire, they should be placed first in a test tube (with stopper) which can then be inserted inside the demagnetizing coil.

Small pieces of steel wire will be attracted to the soft iron core when the circuit is switched on, but most pieces will drop off when the current is turned off. This loss of attractive power, however, depends very much on the softness of the iron core and steel wire pieces. In reality both materials will probably contain a limited degree of hardness, and a few pieces of wire will remain attached to the core when the current is turned off.

Using two cells in the circuit the student will note the increased brightness of the bulb, and will probably suggest that 2 cells produce more electricity than one. It is therefore not surprising to note that the attractive power of the coil is increased, although not doubled. In a typical experiment a coil attracted approximately 30 pieces of wire with one cell, and 40 pieces with 2 cells in the circuit. (A check with an ammeter showed that the current was 0.22 and 0.30 amps in the two cases concerned).

A normal flashlight cell (1.5 volts) is capable of producing about 4 amps in a circuit without a bulb, while a transistor cell (1.5 volts) will produce about 6 amps. However, experimenting without bulbs in the circuit is not recommended since the cells deteriorate very rapidly. With a bulb in the circuit both types of cells produce approximately the same current (0.2 amps).

(ii) Hard steel is more difficult to magnetize than soft iron, but once it is magnetized it tends to retain its magnetism. The hard steel core will probably not attract as many pieces of steel wire when the current passes through the coil, but when the current is switched off far more pieces of wire will remain attached to the core. The hard steel core thus becomes a permanent magnet, whereas the soft iron core only takes up magnetism temporarily.

(iii) It is found that the attractive power of the nail increases as the number of layers of current carrying wire increases. A typical experiment produced the following results:

No. of Layers On Coil	Pieces of Wire Attracted (Average of 3 trials)
1	5
2	16
3	24

The sensitivity of the experiment can be increased by using smaller pieces of steel wire, by increasing the number of cells used from 2 to 3, and by increasing the length of each layer of turns (e.g., from 3 to 5 cms). It is in fact interesting to perform a similar experiment to note how the attractive power of the iron core increases as a single layer of turns increases in length (e.g., from 2 to 4 to 6 cms).

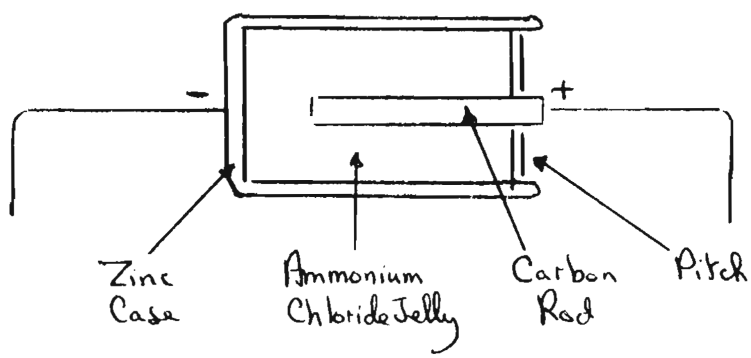
(iv) A coil without a core appears unable to attract small pieces of wire. This does not mean that magnetic attraction is not created by the current in the coil, but simply that if any magnetism is produced it is incapable of attracting the small pieces of wire.

This becomes clearer when a long piece of steel wire is held so that it reaches into the center of the coil, for on switching on the current the wire is drawn up into the coil. The magnetic power of attraction within the coil must be greater than that outside it.

(v) Make sure that the compasses are placed well away from iron masses (pipes, etc.) which will affect the compasses. It will be found that a South Pole is attracted by a North Pole, but repelled by a South Pole. Similarly a North Pole is attracted by a South Pole, but repelled by a North Pole. In other words the student will find that unlike poles attract while like poles repel one another.

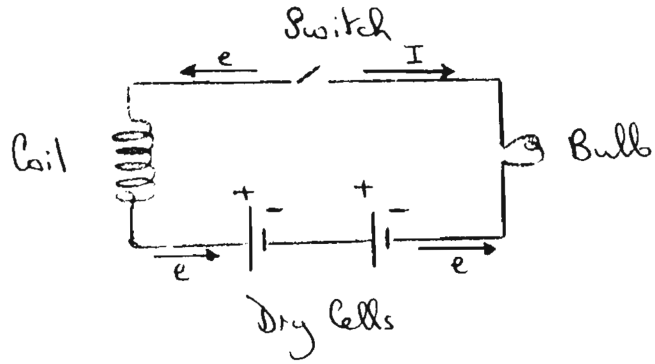
(vi) The current carrying coil behaves in very much the same way as the magnet with one end of the coil attracting the North Pole of the compass needle, and the other end of the coil repelling it. On reversing the cells in the cell holder it will be found that the coil behaves once again like a magnet, but in this case the end of the coil which previously behaved as a North Pole now behaves as a South Pole. This is an important observation which should be discussed with the students for it clearly indicates that the current in the circuit must have a specific direction which is changed by reversing the cells.

This is a good point at which to strip down a dry cell for your students. Point out the relation between the positive sign (+) and the carbon rod and the negative sign (-) and the zinc case.



You may point out that we have no way yet of knowing in which direction the current flows. However, point out that historically scientists guessed that it flowed round a circuit from the carbon rod (+) to the zinc case (-), and that we refer to such a flow as the Conventional Current. Indicate that present day knowledge suggests the flow (electron flow) is in fact in the opposite direction around the circuit from the zinc case (-) to the carbon rod (+), and it will be this direction which we will record on future electrical circuits.

Many students will have found the drawing of circuits to date somewhat tedious, and this will be a good point at which to introduce the representative type of drawing below.

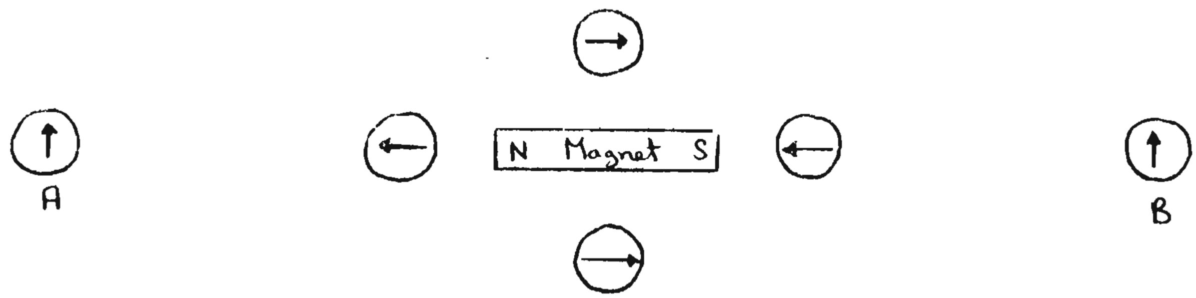


e = electron flow

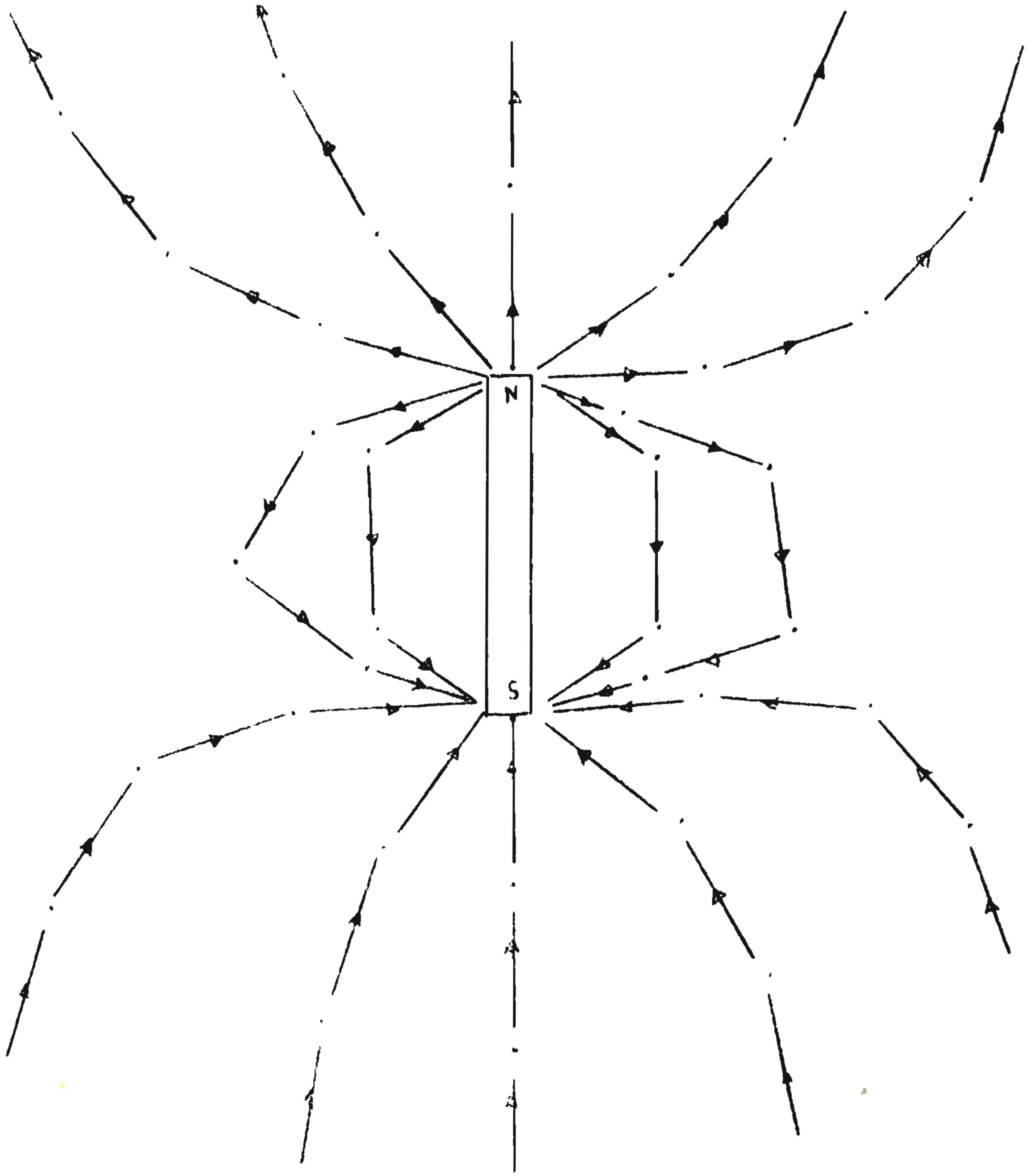
I = Conventional Current

5.12 Magnetic Fields

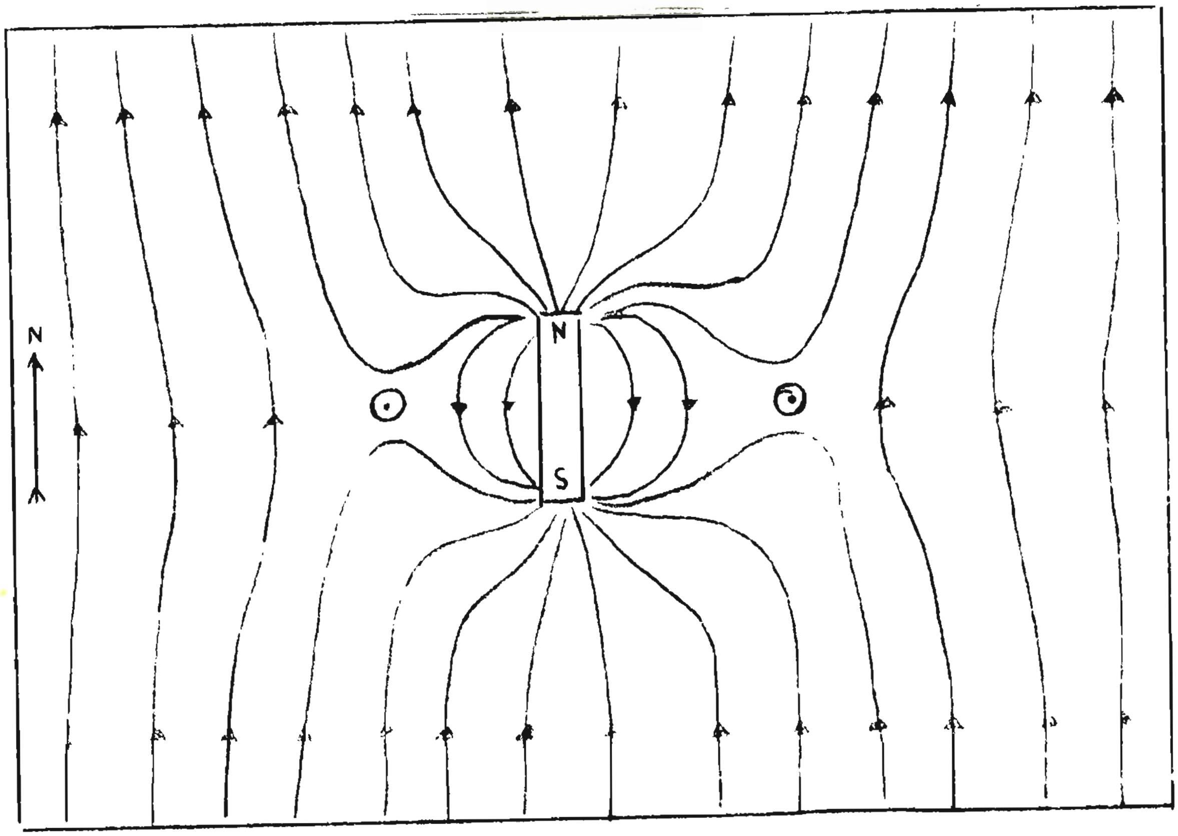
(i) Placed close to the magnet the compass needle points in set directions under the influence of the magnet (see diagram). Only at relatively large distances from the poles is the needle free to point in a North/South direction (A and B).

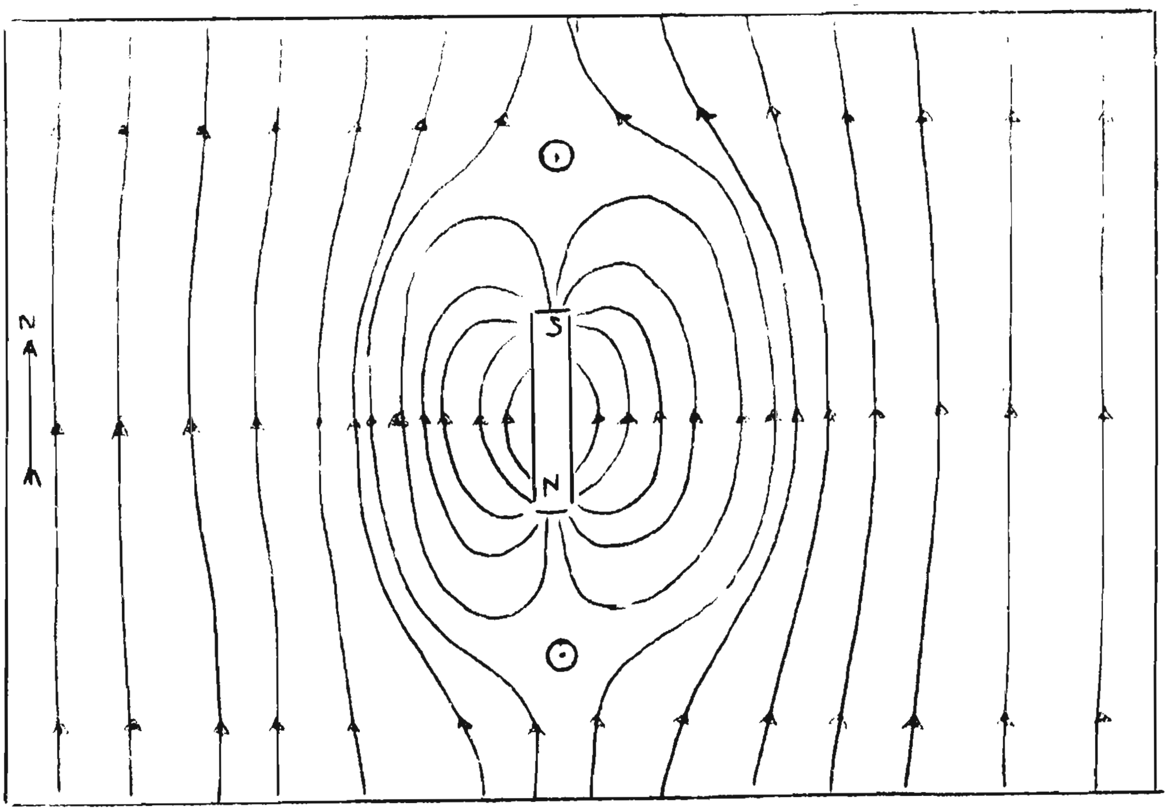


A sketch of the whole magnetic field tends to be more informative, and the result of a typical experiment is indicated in the following diagram. Smoother field lines are produced if a smaller compass is used or a longer magnet (two joined end to end, to double the length), while the stronger the magnet used the better results, for the effect of the Earth's field does not complicate the student's observations.

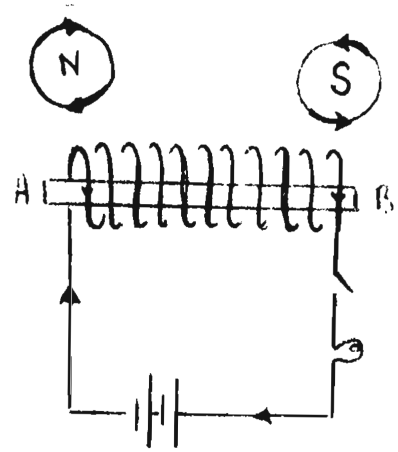


The diagrams that follow indicate the effect of the Earth's field on that of the magnet, causing the creation of neutral points ⊗ where the two fields oppose and cancel one another out. When a magnet is relatively strong such neutral points are created some distance away from the magnet, probably beyond the student's field of observation. However, with a weak magnet they will appear close to the magnet, complicating the picture observed.

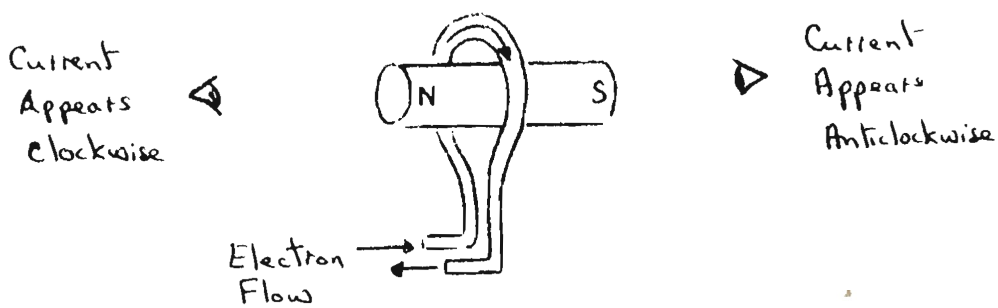

N
S
N


S
N
N

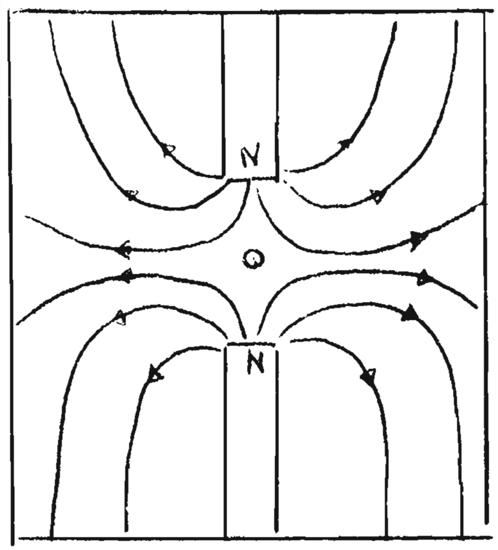
(ii) The magnetic field around the current carrying coil will have the same appearance as that around the magnet. If the preferred direction of the current (the electron flow) is seen to be clockwise at one end of the coil (A) investigation will show that the end of the coil acts as a North Pole. At the opposite end (B) the preferred direction of the current will be in an anticlockwise direction, and investigation will show that this end of the coil acts as a South Pole.

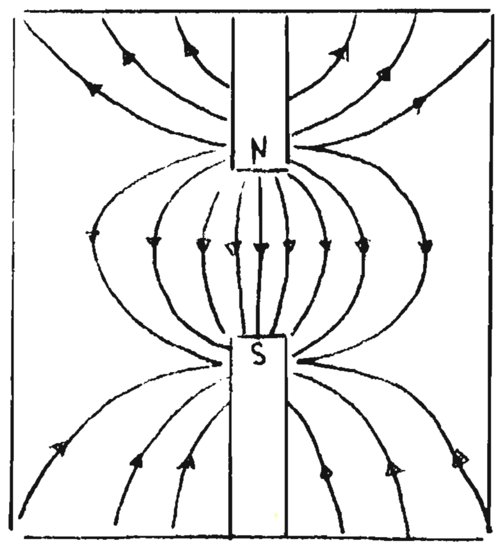


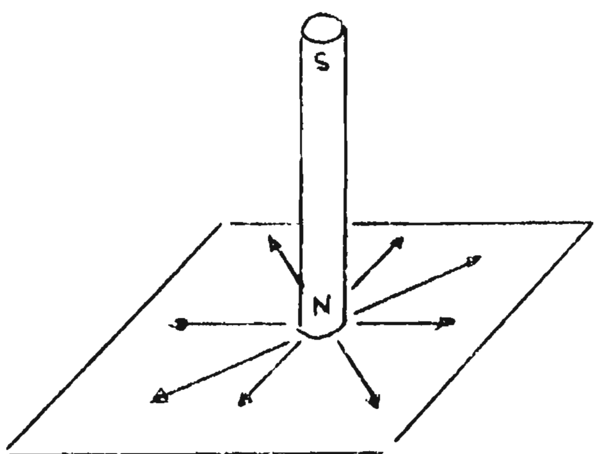
Reversing the direction of the current in the circuit will alter the polarity of the coil ends, but it will still be found that a clockwise current produces a North Pole and an anticlockwise current produces a South Pole.



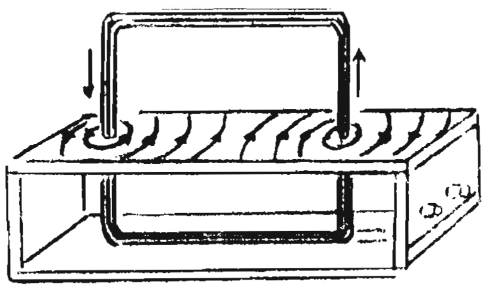
(iii) The primary aim of investigating the fields close to the poles of the magnets is for the student to realize the nature of the field created between a North and South Pole, for such a field is used subsequently to exert forces on current carrying conductors, and to create motion in moving coil galvanometers and simple motors. It is also important that the student should recognize the 3 dimensional nature of a magnetic field, and this tends to emerge from the investigation of the field around a single pole, when the magnet is stood vertically on its end. Typical patterns in the vicinity of the poles are sketched below. The almost linear field between unlike magnetic poles, and the radial field around a single pole, should be emphasized.

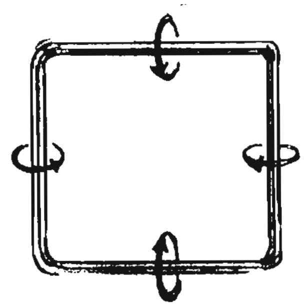




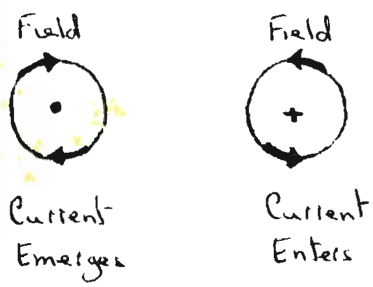


(iv) The compass indicates that the magnetic field around the sides of the coil is such that it encircles the conductors making up the sides. On one side of the coil (A) the field is anticlockwise when viewed from above, and on the other side (B) it is clockwise. This change is to be expected





since the current flows downwards on one side (A) of the coil and upwards on the other side (B). A simple rule emerges if you consider the appearance of the field from above in relation to a cross-section of the current carrying wire. If the current (electrons) emerges from the cross section $\odot$ the field produced is clockwise, whereas if the current enters the cross section $\oplus$ the field produced is anticlockwise.



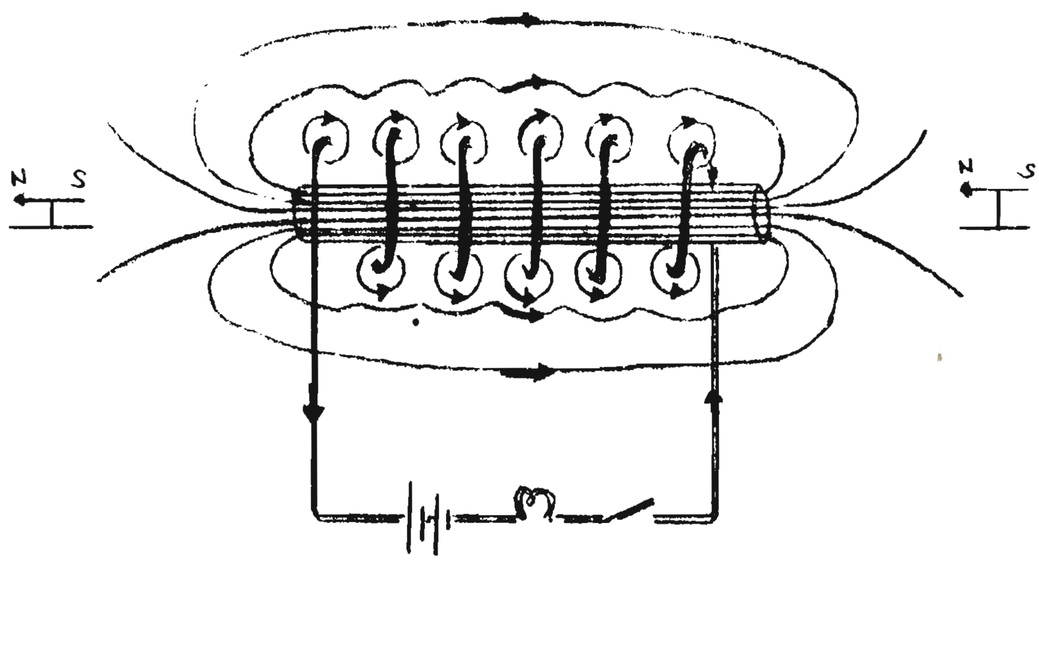
This rule may be checked by placing the compass immediately above, and then immediately below, the horizontal wires forming the top of the coil. The compass will tend to rotate at right angles to the wire (dependent on the strength of the current), and will face in opposite directions above and below the wire.

Compass above Wire

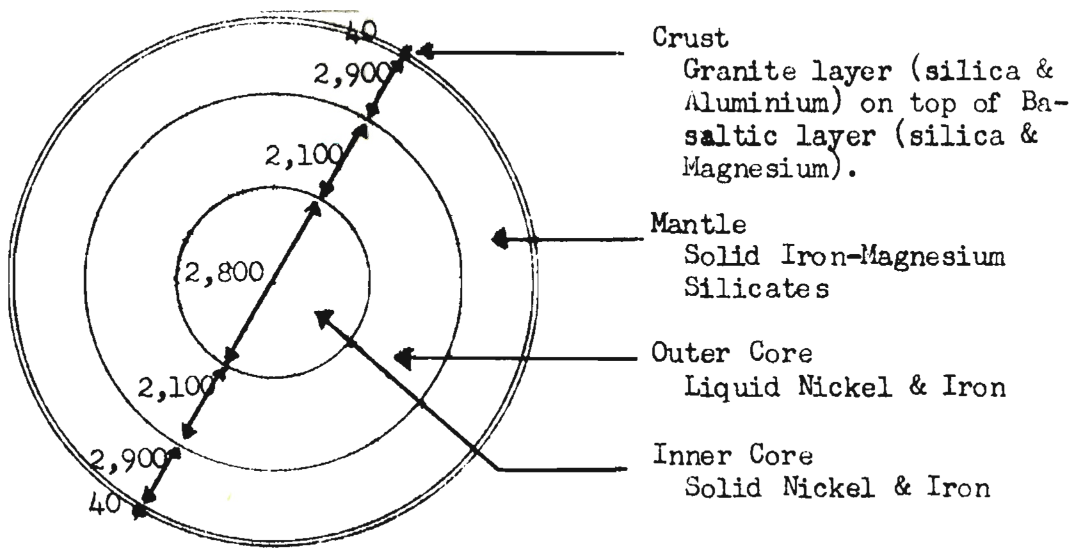
Compass below Wire

As would be expected, reversing the direction of the cells, and hence the current, reverses the direction of the field, but the rule discussed above still holds.

This rule explains the direction of the magnetic field created by a multipurpose coil. The field around each turn of the coil can be predicted, and since the turns are all close to one another one might anticipate that fields created by individual turns will reinforce one another as indicated in the diagram below.

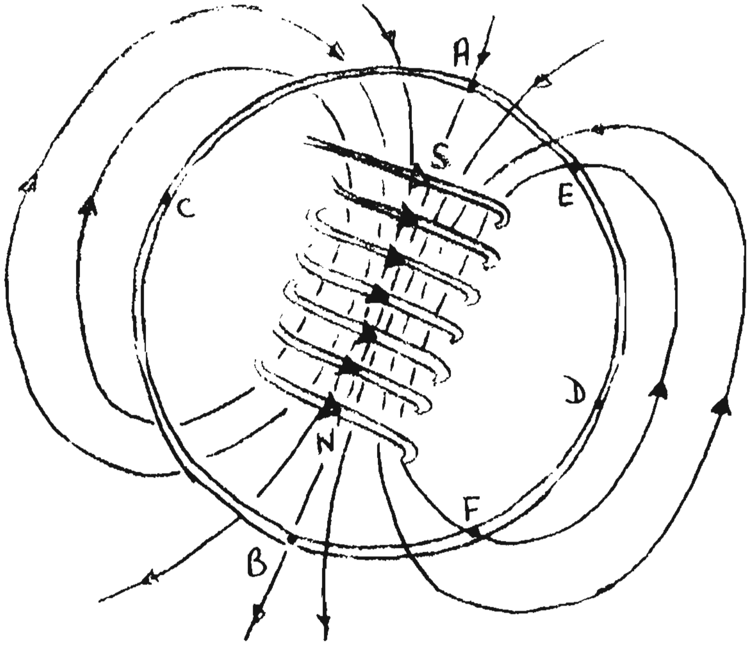


This would be an appropriate point at which to discuss the Earth's magnetic field with your students. Look at the composition of the Earth, and point out that under the Earth's surface there is a great deal of iron, amongst other things, and that much of this is in a liquid state. If motion occurs within the liquid iron this could give rise to electric currents, which in turn would produce strong magnetic fields due to the existence of vast quantities of iron.



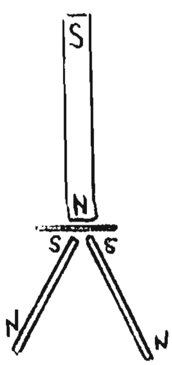
Diameter 12,900 kms

Such currents are likely to be somewhat complex. However, a simplified theory might give us some idea of what is happening. The following diagram illustrates a hypothetical current carrying coil within the Earth which would create a magnetic field very similar to that which we know on Earth.



A compass at the point A (the Earth's magnetic North) would point directly to the South Pole of the coil. The term the Earth's magnetic North Pole may therefore be somewhat misleading, but it simply means the point towards which the North Pole of a compass needle points.

When the two wires are suspended from the bottom of the cylindrical magnet the lower ends are observed to repel one another sideways in much the same way as like poles repel on another. The North Pole of a separate magnet placed close to the wires causes both free ends to be repelled, suggesting that the ends are acting like North Poles. This is confirmed by the attraction of both free ends towards a South Pole. Other small pieces of



wire can be attached to the free ends indicating that the two wires are exhibiting behavior identical to that of magnets, although the magnetism

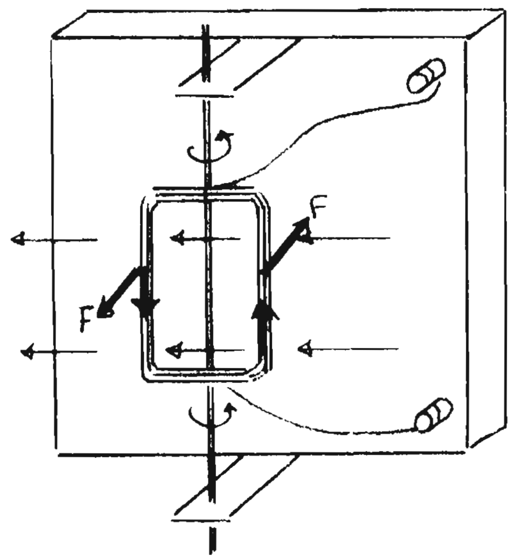
is lost once the wires are separated from the magnet. We describe this behavior as magnetic induction, the permanent magnet temporarily inducing magnetism in the steel wire. It is interesting to place a piece of paper between the magnet and wire when performing the above experiment since this shows that magnetic induction can take place without actual contact between the metals.

Having performed this experiment students should be able to hypothesize that magnetism will be induced in iron objects lying in the Earth's magnetic field. This is found to be so in practice with the Northern end of the object developing a magnetic North Pole.

5.13 Forces on Current Carrying Conductors

(i) The rolling conductor experiment confirms the theory put forward, the conductor rolling forward or backward according to the rule summarized by means of the thumb and two fingers of the right hand. Reversing the current through the roller reverses its direction of motion.

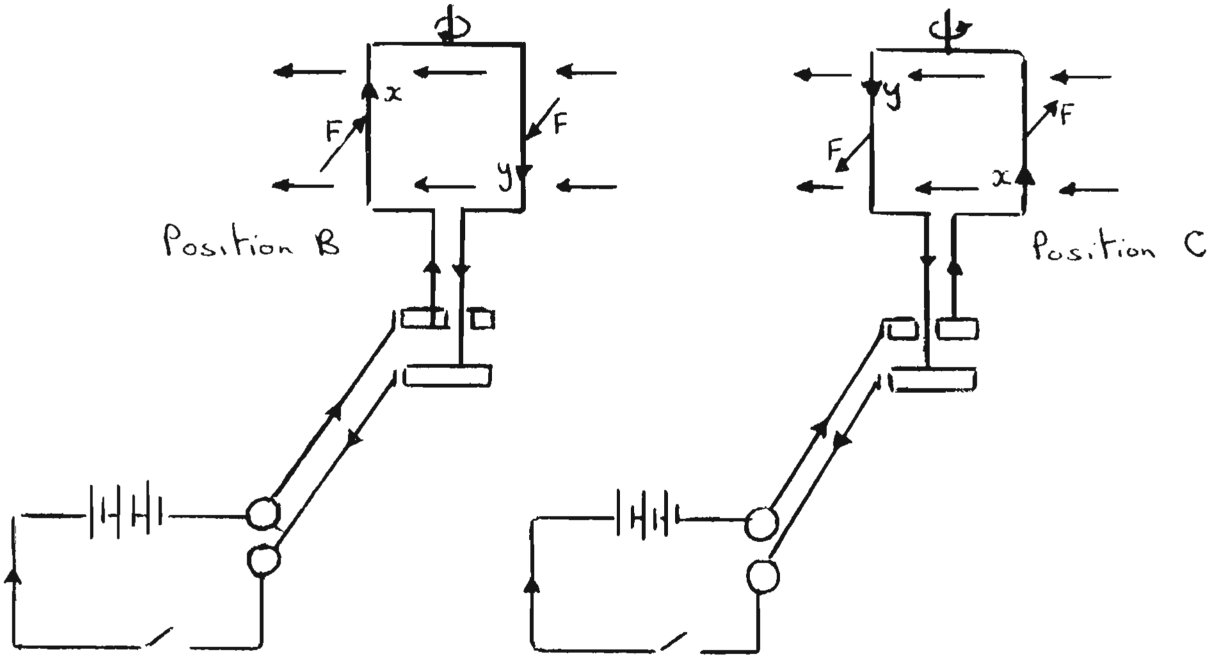
(ii) The direction of motion of the coil is as one would predict. Hence in the diagram below one would predict an anticlockwise motion of the coil as viewed from above. When the coil is displaced from its original



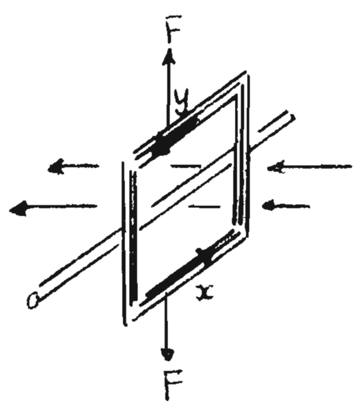
position it causes the spring to create an equal and opposite force to balance it. If the coil is considerably displaced the balancing force of the spring must be large, and hence the force due to the current must also be large. The displacement of the coil is thus a measure of the strength of the current carried by the coil.

(iii) Connecting the motor coil to the dry cells by means of the AC terminals it follows that regardless of the position of the coil the current will always flow through the coil in the same way. In the instance illustrated

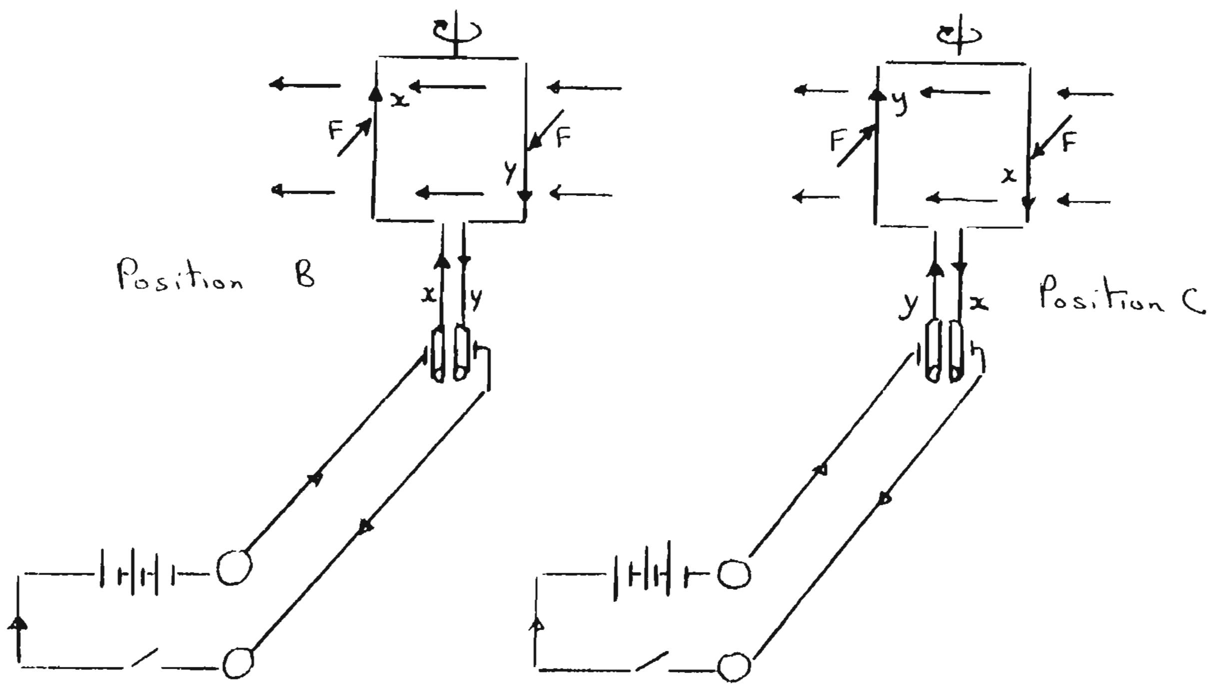
that is up arm x and down arm y. It is therefore not too surprising that



in position C the coil rotates in exactly the opposite direction to when it is in position B. In position A there is no tendency for the coil to rotate at all, since the force created on the coil cannot exert a couple to rotate the coil.



However, when the motor coil is connected to the dry cells by means of the DC terminals the coil is noted to rotate continuously in one direction. This is because the current is carried to, and from, the coil by means of spring contacts touching lightly against separate halves of a split cylinder, each half being insulated from the other. As the coil rotates each contact touches first one half of the split ring and then (180^{o}later) the other, causing the current in the coil to move first in one direction (up side x, and down side y) and then (180^{o}later) in the other direction (up side y, and down side x). From the diagram it follows



that the forces resulting from the interaction of the magnetic field and current always drive the coil in the same direction, regardless of the starting position (B or C). However, when the coil is placed in an intermediate position (A), in a vertical plane, it will still remain stationary. The split cylinder device is rather special, in that it makes continuous rotary motion possible, and is generally referred to as a commutator.

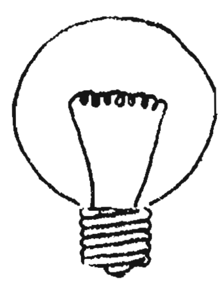
5.20 DETECTION AND PRODUCTION OF ELECTRICITY

5.21 Detection of Electricity

(i) The introductory experiment is intended to illustrate the fact that detectors vary in sensitivity, and that students should interpret observations carefully. Thus in failing to detect the existence of a current in an electrical circuit one would conclude that with the available apparatus, and under the existing conditions, no current was detected, and not that no current existed. The importance of this attitude to any aspect of physics cannot be emphasized too strongly.

With only 1 cell in the circuit the larger bulb (6.2 v) will glow faintly, while the small bulb (2.5 v) will remain unaffected. With 2 cells in the circuit the large bulb will be reasonably bright. The small bulb will just show the faintest glow if the cells are in good condition, or if they happen to be transistor cells, otherwise no reaction will be observed. With 3 cells in the circuit both bulbs will light up, but the large bulb will be far brighter than the small bulb. There would appear to be very little doubt that electricity flows in all three circuits, and one must conclude that the small bulb is not always sufficiently sensitive to detect its existence.

Looking at the bulbs with a hand lens students should be able to see that the filaments are in fact fine coils, with the larger bulb having the larger coil. It follows that the brightness of a bulb depends not only on the current passing through it, but also on the nature of the filament. This will lead the student nicely into later experiments on resistance of wires. (The resistance of the small bulb is about 1 ohm, and that of the larger bulb a little less than 3 ohms).



(ii) Unlike the bulbs used to date the neon bulb does not light up when connected into the circuit with 3 dry cells. A close look at the bulb shows that instead of the usual filament it has two electrodes, and if a current is to pass through the bulb it must jump from one electrode to the other. At this point it is suggested that you join about 13 dry cell holders (39 dry cells) end to end in series with the neon bulb. It will be noted that with an accumulative voltage of about 60 volts the neon bulb is actually illuminated. The interesting point to be observed is that a glow is created around only one of the wires, not both, and that this is always the wire connected to the zinc case (negative) of the dry cell. It may be noted that the neon bulb has a very important role to play in demonstrating the link between electrostatics and current electricity.

The tester provided is very similar to those used regularly by electricians. When inserted into the electrical plug nothing happens until the finger is placed on the rear end of the detector, and then a bright glow is observed around the two wires inside the tube. In this instance both electrodes glow since we have an AC supply, not a DC supply in the case of the neon bulb on its own.

(iii) Without the resistor in the circuit the bulb lights up and the galvanometer needle is deflected demonstrating that they are both reacting to the same thing (an electrical current)but in different ways.

With the addition of the resistor to the circuit the bulb no longer lights up, but the galvanometer still shows the existence of a current. The tangent galvanometer is clearly a much more sensitive device than a bulb for detecting the existence of electricity. The following typical results may be of interest.

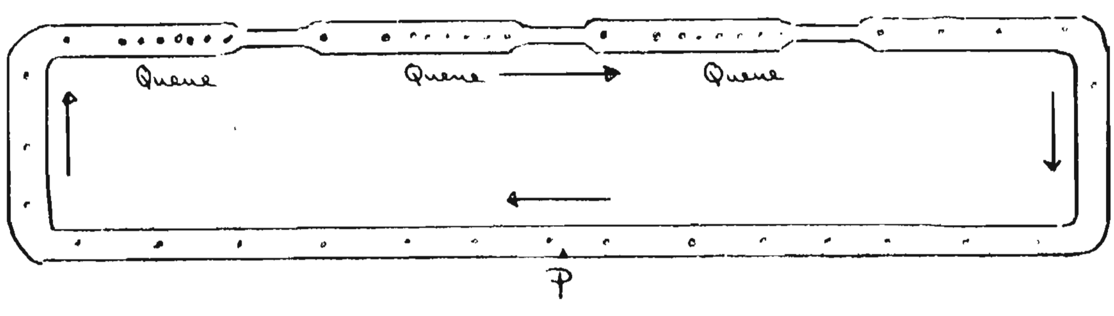
Circuit	Galvanometer Deflection
1 Cell + Resistor	45 degrees
2 Cells + Resistor	65 degrees
1 Cell, No Resistor	80 degrees

The results indicated in the table below were obtained using the suggested combinations of bulbs in the moving coil circuit. They indicate that increasing the number of bulbs in series in a circuit decreases the current, suggesting that the resistance of the circuit to the flow of current increases with increasing number of bulbs in series. Increasing the number of bulbs in parallel has the converse effect, increasing the current, presumably due to a lowering of the total resistance in the circuit.

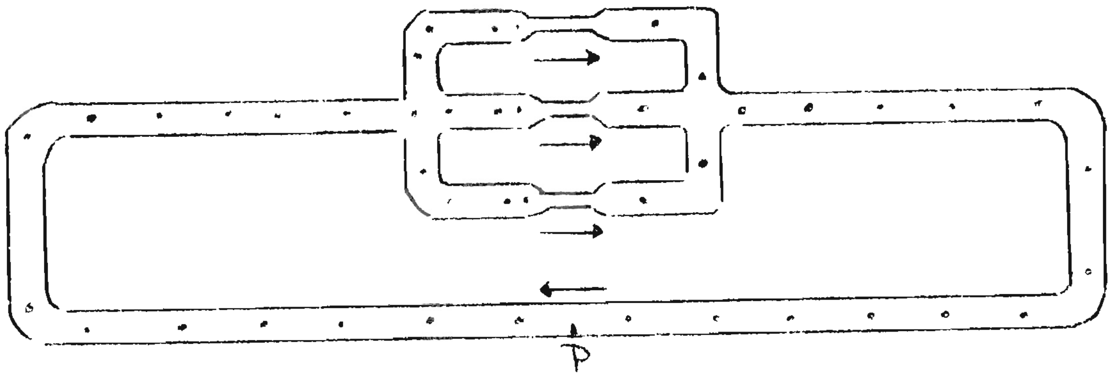
Circuit	Galvanometer Deflection
3 bulbs in series	7 degrees
2 bulbs in series	9
1 bulb	13
2 bulbs in parallel	20
3 bulbs in parallel	25

A general discussion of several analogies can be extremely valuable at this stage. No analogy will be perfect, and it is important that the student should realize the limitations of any comparison. One might discuss the effect of narrow pipes on the flow of water in a circuit, the effect of narrow road sections on the flow of traffic around a road circuit, or the effect of hurdles on the pace of athletes running around a 400 meter track. Restrictions will in all cases reduce the rate of flow.

Take the specific example of a road circuit. Spread cars out equally around the circuit, and then set them all in motion at the same speed. Narrow restrictionswill result in time lost in queues, and the greater the number of restrictions in series the greater the time that will be lost. An observer at any point P would thus observe fewer cars per hour as the number of restrictions increased. (Athletes running around a track one after the other would be subject to similar restrictions by hurdles.)



The waiting time at any one restriction can be reduced considerably if alternative parallel routes are provided for the cars, even if each of these alternatives is in itself a restriction. An observer at point P would observe more cars per hour as the number of parallel routes was increased.



5.22 Production of Electricity

(i) Both the salt solution and the vinegar (but not the water) when placed in the cell are capable of producing electricity, and it is noted that when used in combination with the zinc case and carbon rod the vinegar produces a larger current than the salt solution.

(ii) The zinc and iron combination of plates produces a deflection of about 70^{o} compared with a deflection of approximately 20^{o} for the zinc and carbon combination in vinegar. For this reason the zinc and iron plates are used for the more detailed observations.

Although the zinc and iron combination produces an immediate deflection of about 70^{o}, this falls off to about 50^{o} in a matter of a few seconds, and then remains reasonably steady. Removing the plates from the water it will be observed that both plates have lost their metallic brightness, and have developed thin coatings on their surfaces. Re-polishing with emery paper soon removes the coating, and the initial 70^{o} deflection of the galvanometer can be reproduced on immersing the plates once more in the vinegar.

Separating the plates the deflection falls off from 50^{o} (at 0.5 cms apart) to 15^{o} (at 7 cms apart), but returns to the original value (50^{o}) when the plates are brought back to the initial spacing. If the plates actually touch one another the deflection falls to zero. Finally, raising one plate on its own, or both simultaneously, from the solution the deflection falls off to zero, but returns to its original value when the plates are completely immersed once again. It would seem that the current produced by a combination of materials depends not only on the separation between the plates, but also upon the opposing area of plates immersed in the solution.

The relative currents produced by the different plate combinations are noted below.

Plates Immersed in Vinegar	Galvanometer Deflection
Zinc, Iron	70 degrees
Iron, Carbon	50
Zinc, Copper	30
Iron, Copper	30
Zinc, Carbon	20

Plates Immersed in Salt Solution	Galvanometer Deflection
Zinc, Copper	40 degrees
Zinc, Iron	20
Iron, Copper	10

It is interesting to note that a zinc, iron combination is less effective than a zinc, copper one, when the materials are immersed in salt solution. This is contrary to what might have been expected from observations with vinegar, and stresses the fact that the nature of the solution, as well as that of the plates, determines the strength of the current produced.

If sulphuric acid (approximately normal, although this is not critical) is available it is well worthwhile making a cell with zinc and copper plates and sulphuric acid, for this combination is capable of lighting a small bulb placed in the same circuit. It will be observed that as gas bubbles form on the copper plate the bulb dims and extinguishes itself. If the plate is tapped the bubbles are released, and the bulb lights up temporarily once again. The addition of a little potassium dichromate to the acid will chemically prevent the accumulation of gas bubbles, and the bulb will remain illuminated.

Zinc and copper plates immersed in distilled water do not produce electricity. However, when immersed in local water they may produce a slight effect due to salts dissolved in the water.

One cell that most students find intriguing can be made from a lemon. Squeeze the lemon to break up the tissue inside, and then insert the copper and zinc plates as far as possible into the juice. A current can be detected in the usual way by means of a galvanometer.

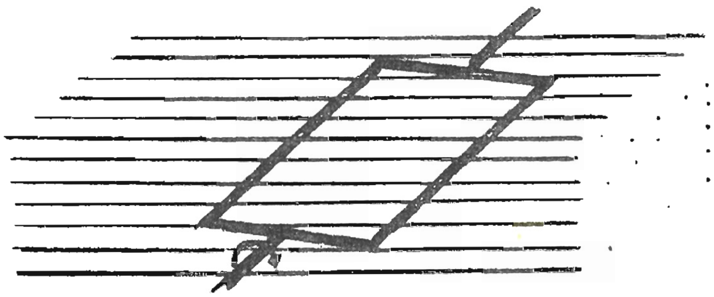
(iii) When the magnet is stationary inside the coil the galvanometer needle remains undeflected. However, when the magnet is removed rapidly from the coil a small deflection is produced indicating that a current is created while the magnet is in motion. It follows that it is the motion of the magnetic field cutting the turns of the multipurpose coil which causes a current to be induced in the multipurpose coil. The series of observations show that the stronger the magnet used, and the more rapid the motion of the magnet, the greater the current that is induced in the coil. The maximum induced current produces a deflection of about 20^{o} in the galvanometer.

On withdrawing the magnet from the coil it is noted that the current induced is in the opposite direction to that induced when the magnet is pushed into the coil, indicating that the direction of the induced current depends on the direction of motion of the magnetic field.

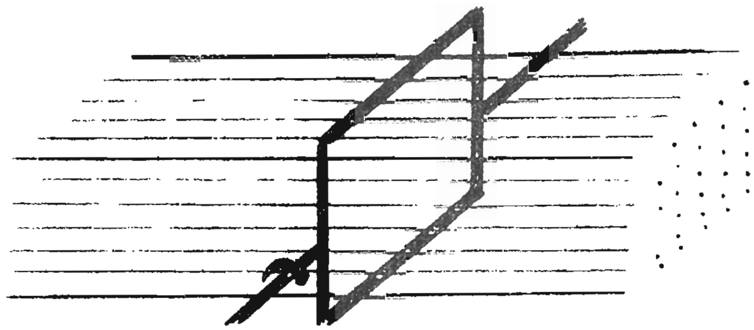
(iv) When the current is switched on in the electromagnet circuit the galvanometer registers a temporary deflection, even though the current is maintained in the electromagnet circuit. This confirms that the induced current is produced by the growth of the magnetic field created, and not by its actual existence. Similarly a current is induced in the galvanometer circuit when the electromagnet circuit is switched off. In this case the magnetic field is collapsing, as opposed to growing, and the induced current is in the opposite direction, as indicated by the galvanometer. When the electromagnet circuit contains a bulb the magnetic field is relatively weak, and the resultant deflection is only about 5^{o}. If the bulb is removed from the circuit the magnetic field produced is much stronger, and the resultant deflection is of the order of 20^{o}.

(v) Connecting the dynamo to the galvanometer by the AC terminals it is found that rotating the coil sharply forward from position (A) the deflection of the galvanometer indicates the creation of a current. Rotating the coil backwards from the same position the deflection is in the opposite direction, indicating that the current produced is dependent on the direction of motion of the coil as it cuts the magnetic field.

Backward or forward motion in position (B) induces very little current, for the coil cuts a minimum cross sectional area of the magnetic field in such a rotation. However, in position (A) the same degree of rotation cuts a large cross sectional area of the magnetic field and the induced current is relatively large.



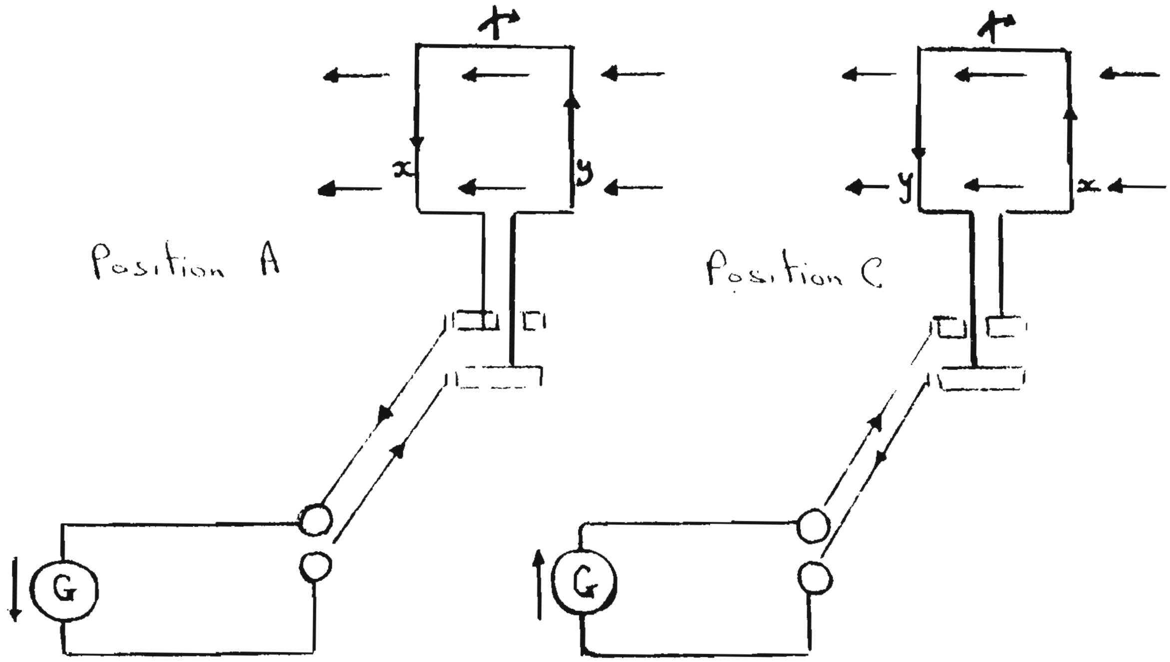
Position A



Position B

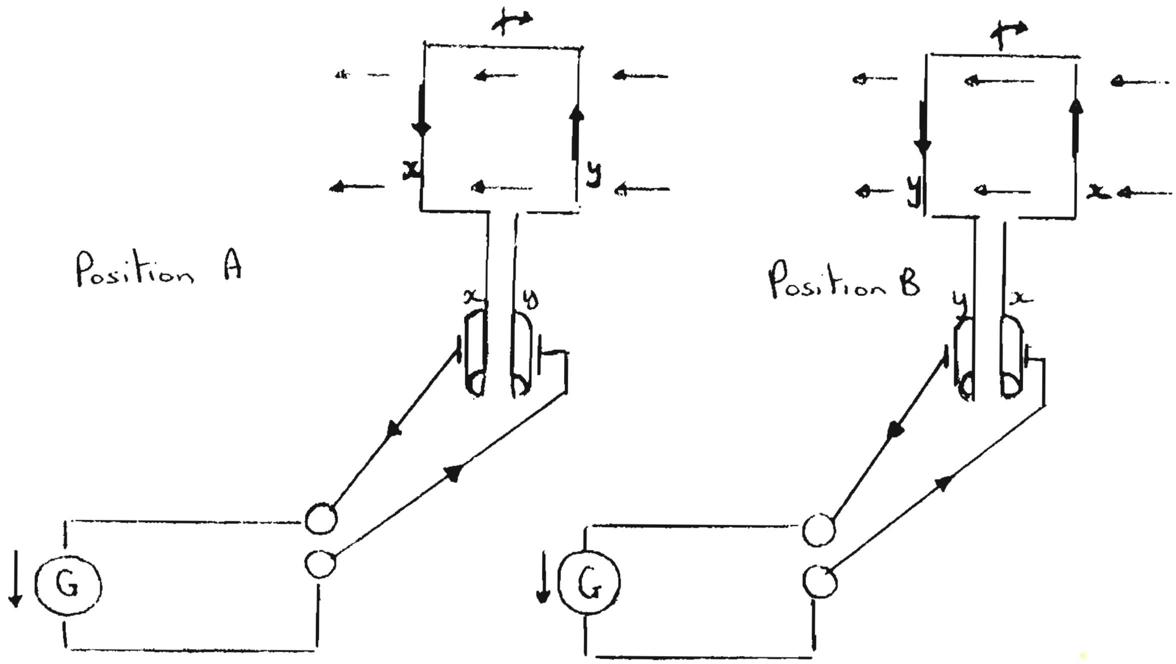
What, however, is surprising to the student is that forward motion in position (C) induces a current in the opposite direction to that produced by the same forward motion in position (A). This leaves only one conclusion, namely that the current induced in the coil in position (C) is in the opposite direction to that induced in position (A). In fact, the induced current moves alternately backwards and forwards as the coil rotates, changing its direction of motion every 180^{o} rotated by the coil. The current passed through the galvanometer from the AC terminals is therefore an Alternating Current.

This behavior is logical. Whenever a side of the coil moves upwards through the magnetic field the current will always be induced in the same direction in the conductor. This means that for every 180^{o} rotated by the coil the direction of the current in a given side (e.g., x or y) must be reversed.



A careful study of the diagram should then explain how from this fact it must follow that the current reverses backwards and forwards through the galvanometer (G).

When the galvanometer is connected to the DC terminals it is noted that the current flows through the galvanometer in the same direction when the dynamo is rotated in the same direction in either position A or position B. The current generated in the sides of the coil (x and y) are exactly the same as before. The only difference is that a different commutator is used. A study of the following diagram should clarify how it is that the current always flows in the same direction through the galvanometer.



The difference between AC and DC current should emerge fairly clearly from this experiment. It is also important that the similarity should also emerge, and this tends to be emphasized by the fact that both the AC and DC currents light up the bulb.